Lecture Series Buenos Aires

18-3-2024 until 22-3-2024

Lecture F4 – Chirped pulse amplification

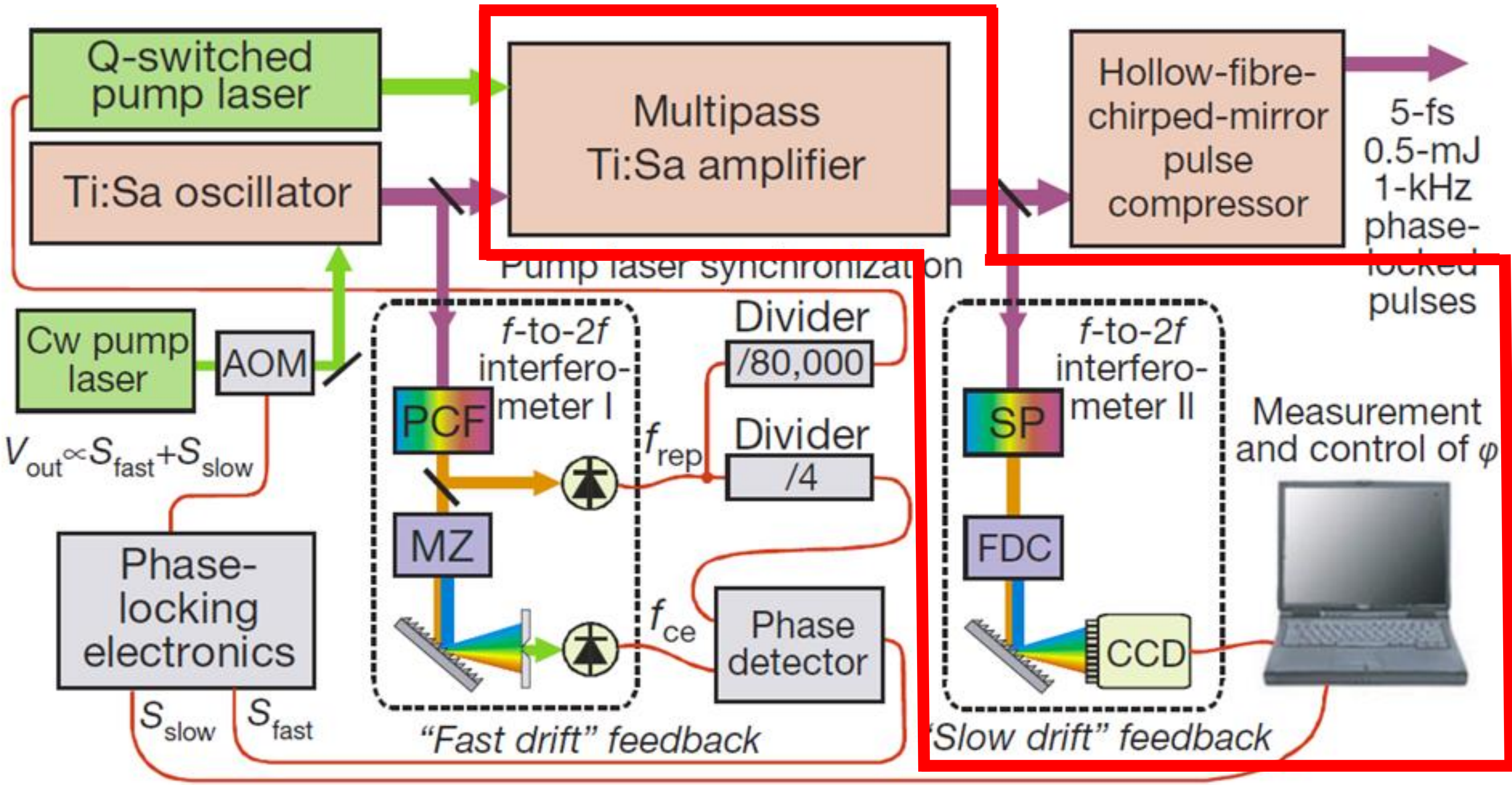
Federico Furch

furch@mbi-berlin.de

Max-Born-Institut

Chirped Pulse Amplification

A state-of-the-art laser system for attosecond science



A. Baltuska et al., Nature 421, 611 (2003)

Chirped pulse amplification (CPA)

Intensity dependence of the refractive index $n(I) = n_0 + n_2 I$

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Volume 55, number 6 OPTICS COMMUNICATIONS 15 October 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES

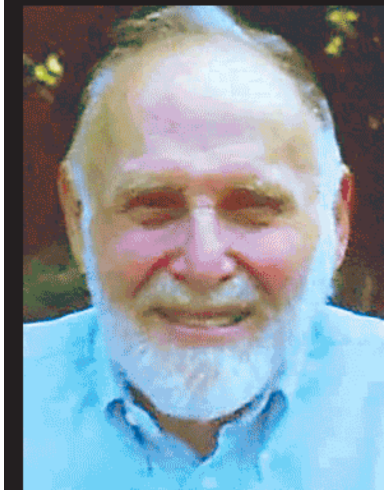
Donna STRICKLAND and Gerard MOUROU

Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA

Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

Nobel Prize in Physics



Arthur Ashkin *(USA)*, **Gérard Mourou** (*FRA)* **and Donna Strickland** *(CAN)* **have won the 2018 Nobel Prize in Physics for their groundbreaking inventions in the field of laser physics**

PHYSICS PRIZE IN NUMBERS

111 Nobel Prizes in Physics awarded from 1901 to 2017

1 double winner, ***John Bardeen***, awarded prize in 1956 and 1972

25 Age of youngest laureate, ***Lawrence Bragg***, awarded prize in 1915

3 Women awarded prize, including ***Marie Curie*** in 1903, and Strickland in 2018

Source: Nobelprize.org

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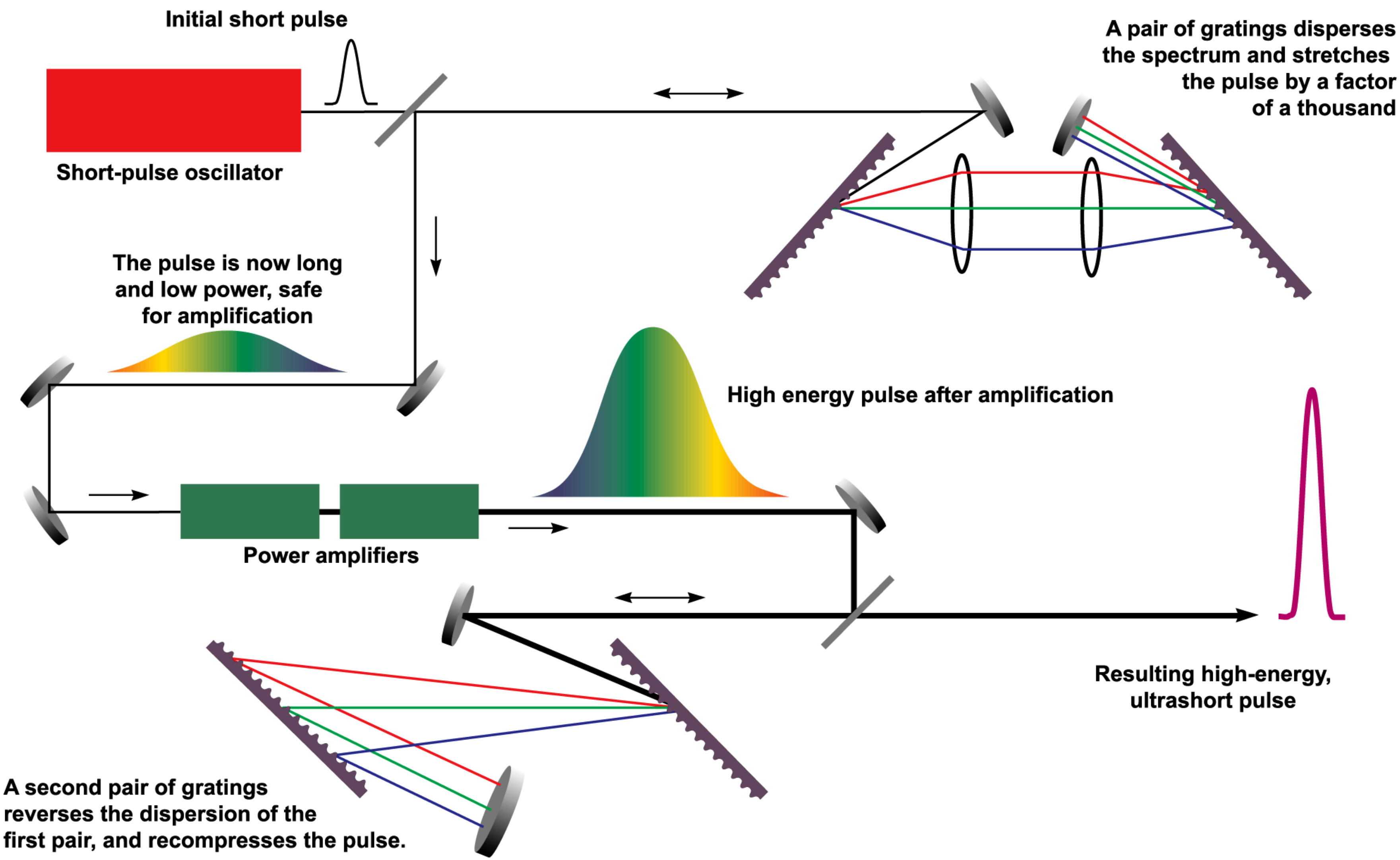
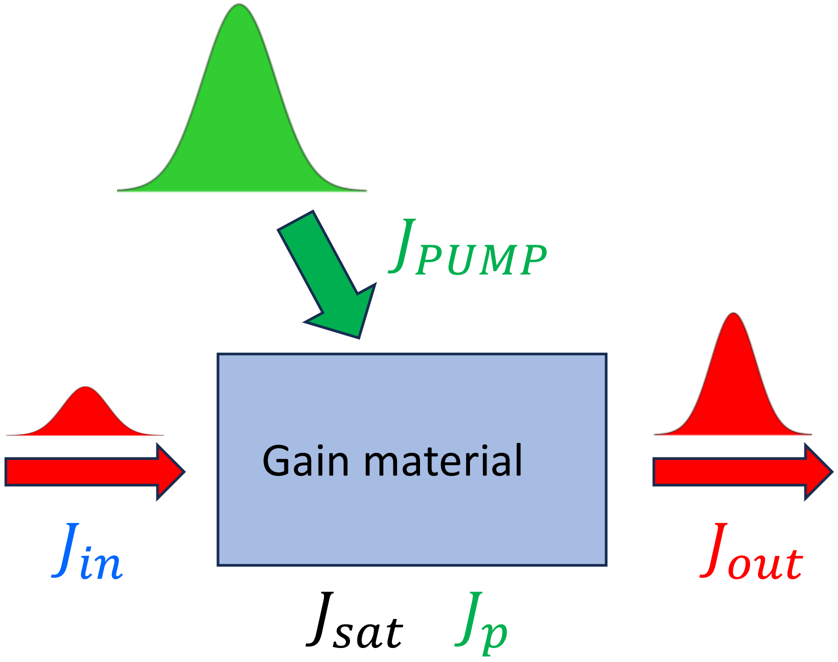


Amplification: single pass



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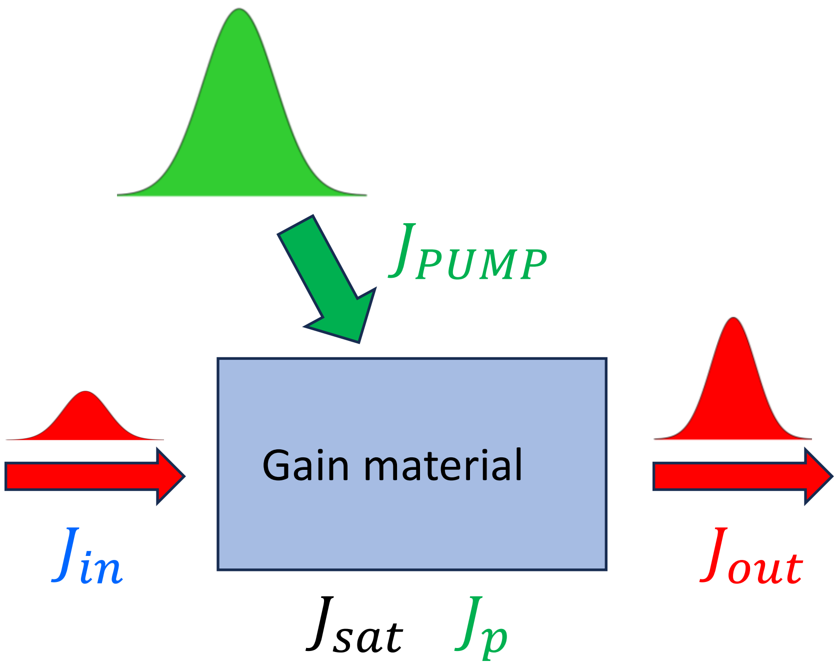
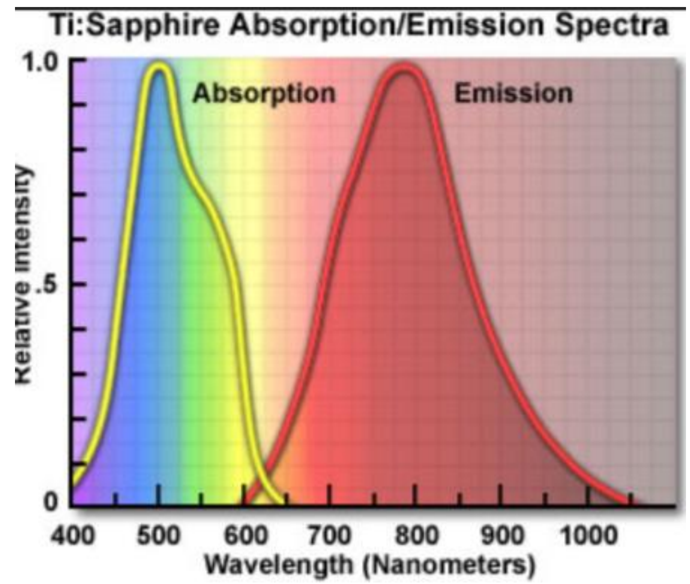
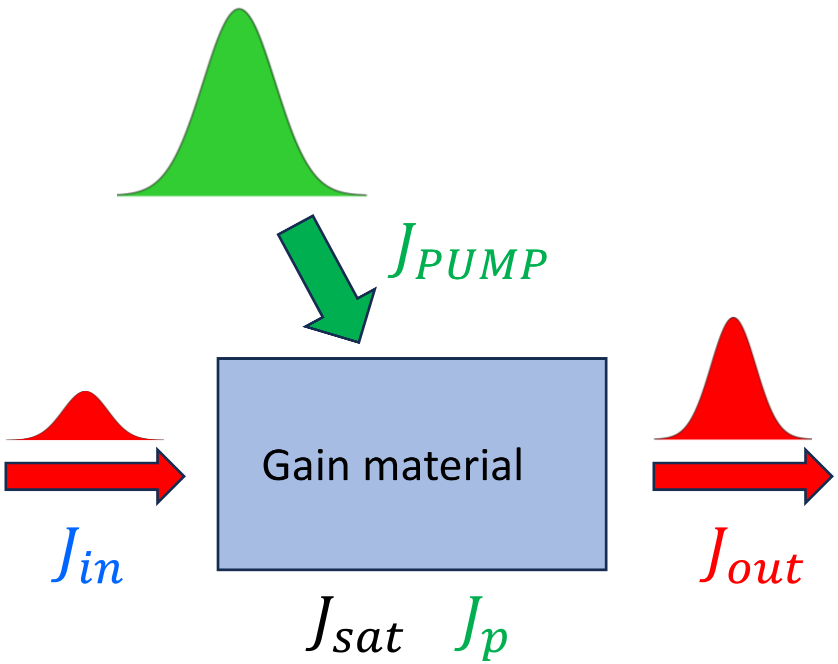


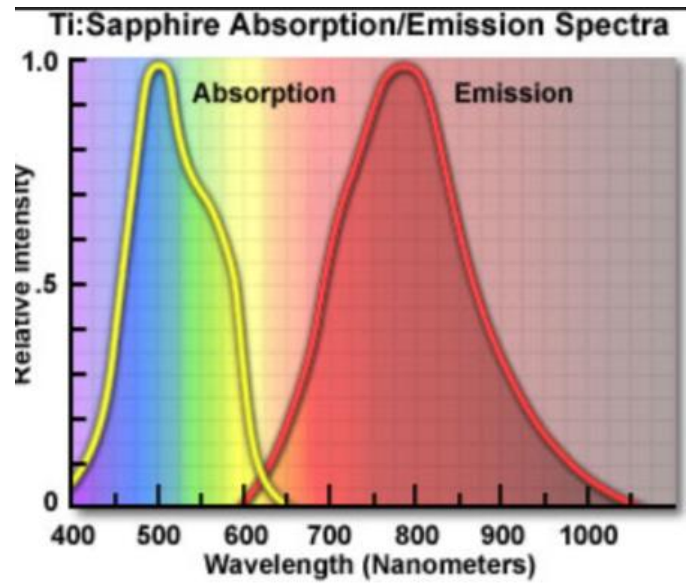


Saturation fluence: $J_{sat} = \frac{\hbar\omega}{\sigma}$

Energy per unit area that leads to significant depletion of the upper laser level, such that than gain reduces to 1/e (≈37%) of the initial value

Amplification: single pass





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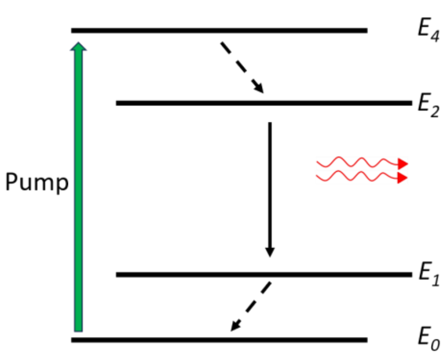
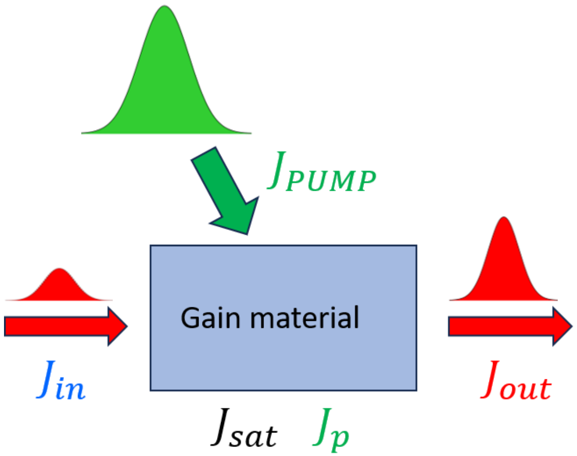


Stored pump fluence (J/cm²)

$$J_p = \frac{\omega_{laser}}{\omega_{pump}} J_{PUMP}$$

Amplification: single pass

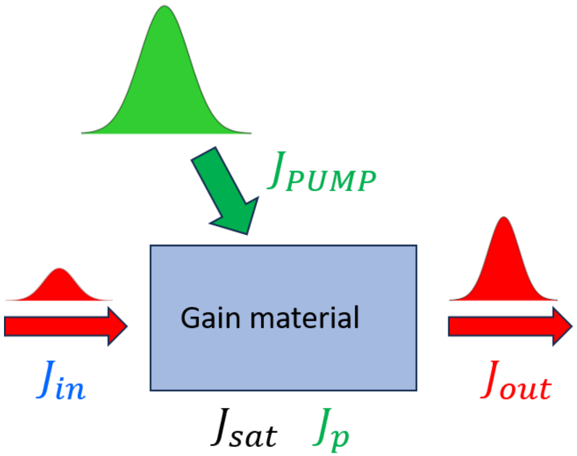


Low intensity: $\frac{dJ}{dz} = g_o J$ exponential growth

Saturation: $\frac{dJ}{dz} = g_o J_{sat}$ linear growth

Intermediate situation: $\frac{dJ}{dz} = g_o J_{sat}(1 - e^{J/J_{sat}})$

Amplification: single pass



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Intermediate situation: $\frac{dJ}{dz} = g_o J_{sat}\left(1 - e^{J/J_{sat}}\right)$

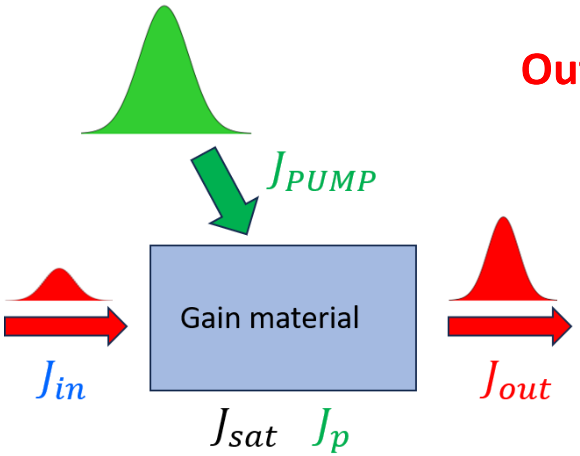
Integrate differential equation and we get the Frantz-Nodvick equation (output of saturated amplifier):

Output fluence (J/cm²) **Input fluence (J/cm²)**

$$J_{out} = J_{sat}\left[\ln\left\{1 + G\left(\exp\left(\frac{J_{in}}{J_{sat}}\right) - 1\right)\right\}\right]$$

$G = exp(J_p/J_{sat})$ Gain, where $g_o L = J_p/J_{sat}$

Amplification: single pass



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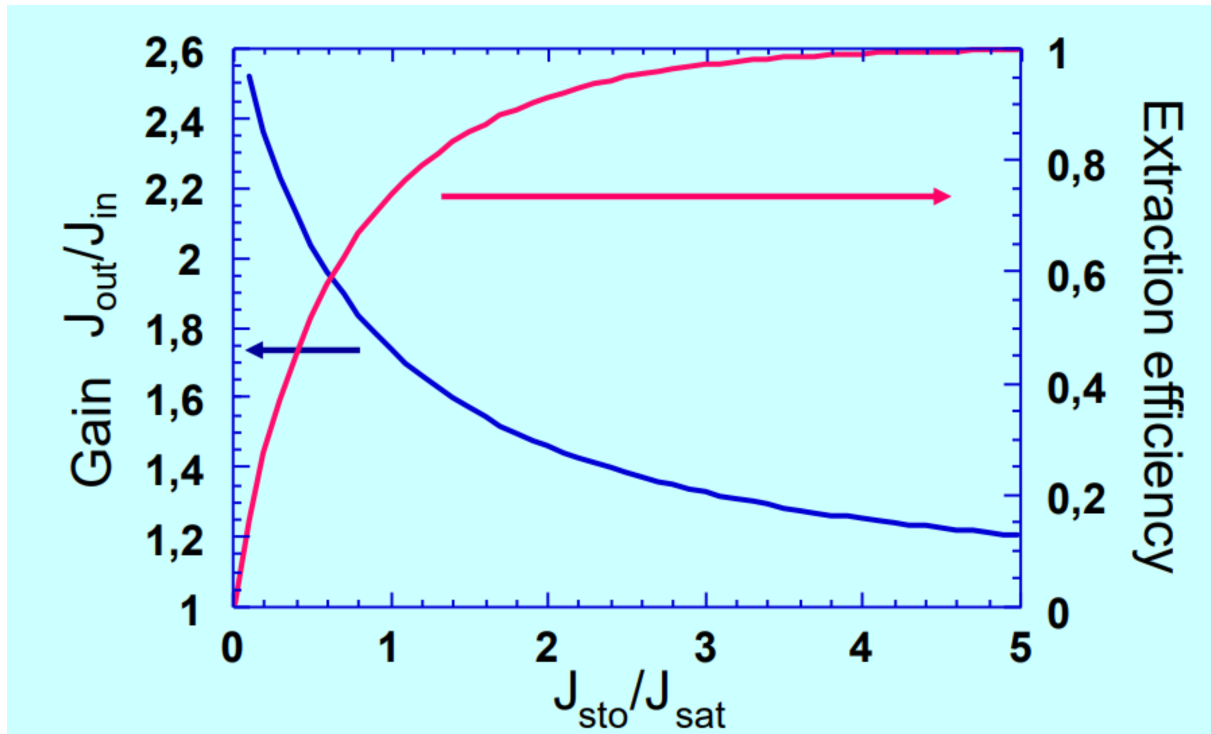
Frantz-Nodvick tells us it is possible to get either high gain and low extraction efficiency, or high extraction efficiency and low gain



From https://www.fuw.edu.pl/~zopt/photonics/UFO_PW/UFO_04_Amplifiers.pdf

Amplification

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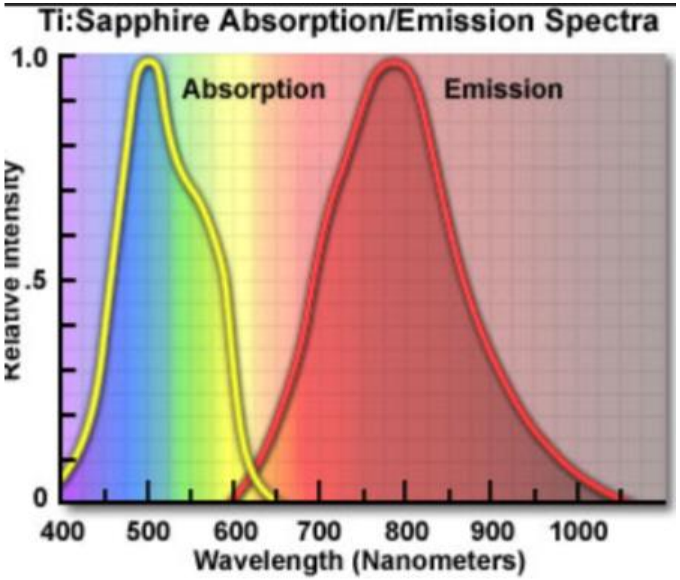
- This equation assumes single frequency, no time dependence.
- In CPA we amplify pulses that have different frequencies appearing at different times (chirp), and saturation fluence is frequency dependent



Amplification

Output fluence (J/cm^2)   Input fluence (J/cm^2)

$$J_{out} = J_{sat}\left[\ln\left\{1 + G\left(\exp\left(\frac{J_{in}}{J_{sat}}\right) - 1\right)\right\}\right]$$

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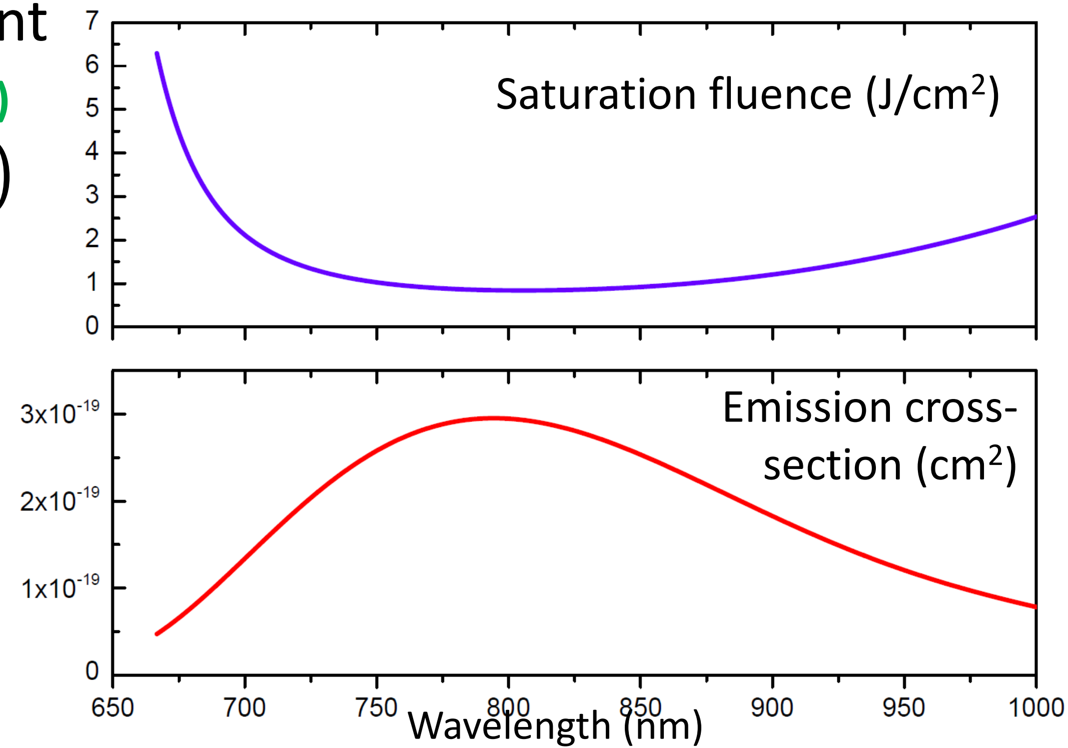
Stored pump fluence (J/cm^2)

Gain $G = exp(J_p/J_{sat})$

Saturation fluence

$$J_{sat} = \frac{h\omega}{2\pi\sigma(\omega)}$$



Chirped pulse amplification (CPA)

$\omega = Kt$

In CPA, the frequency that is amplified becomes a function of time

C. Le Blanc et al., Optics Communications 131, 391 (1996)

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In CPA, the frequency that is amplified becomes a function of time

Assume $J_{in}(t)$ and differentiate the equation for J_{out} with respect to time

Input intensity (J/cm²)

Output intensity (W/cm²)

$$I_{out}(t) = \frac{\exp\left(\frac{J_{in}(t)}{J_{sat}}\right)\left(G(t)I_{in}(t) + J_{sat}\frac{\partial G(t)}{\partial t}\right) - J_{sat}\frac{\partial G(t)}{\partial t}}{1 + G(t)\left\{\exp\left(\frac{J_{in}(t)}{J_{sat}}\right) - 1\right\}}$$

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Input intensity (J/cm²)

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extracted fluence (J/cm²)

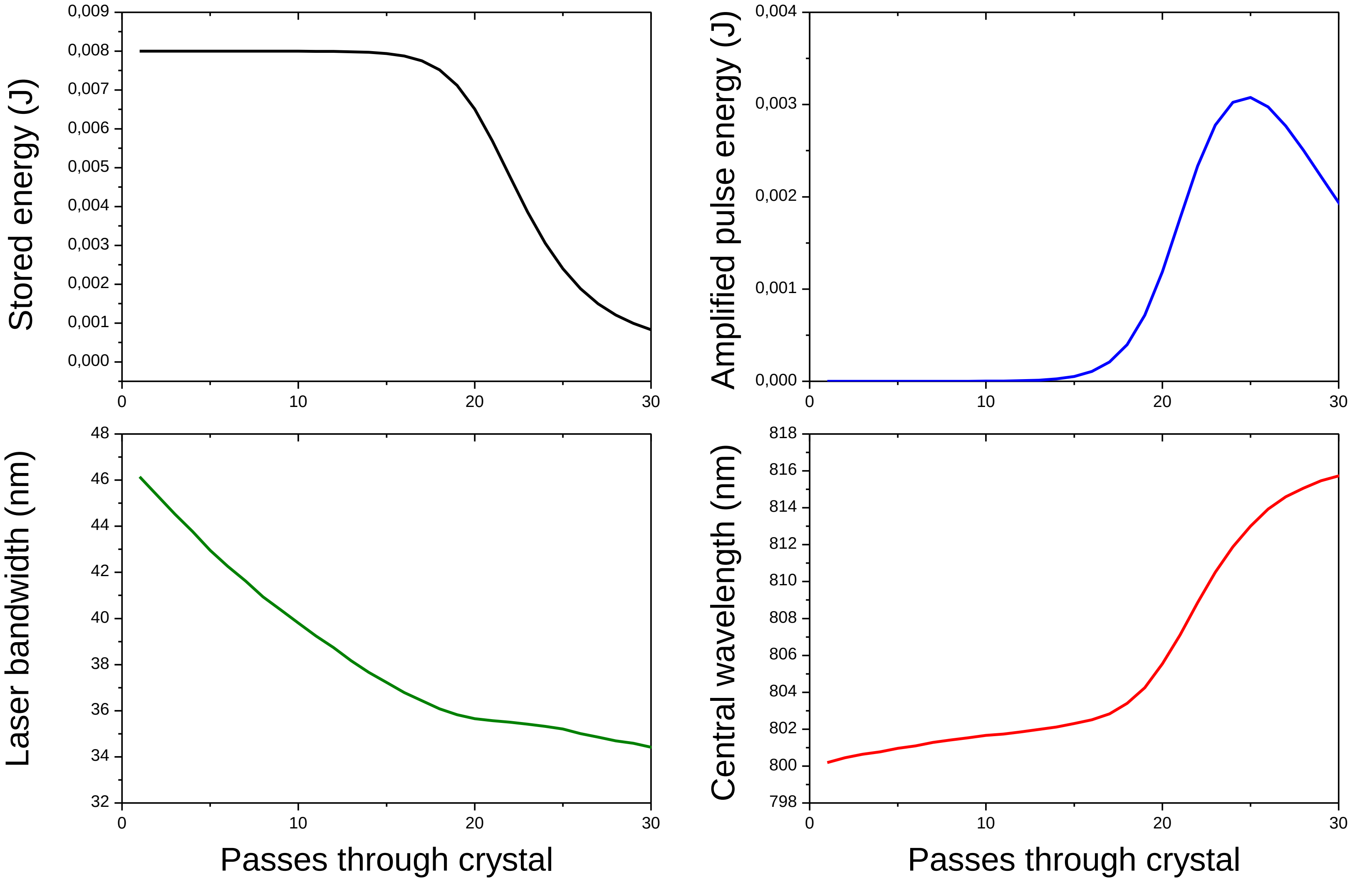
$$G(t) = exp\left(\frac{J_{s0} - (J_{out}(t) - J_{in}(t))}{J_{sat}}\right)$$

And take into account gain depletion during amplification

C. Le Blanc et al., Optics Communications 131, 391 (1996)

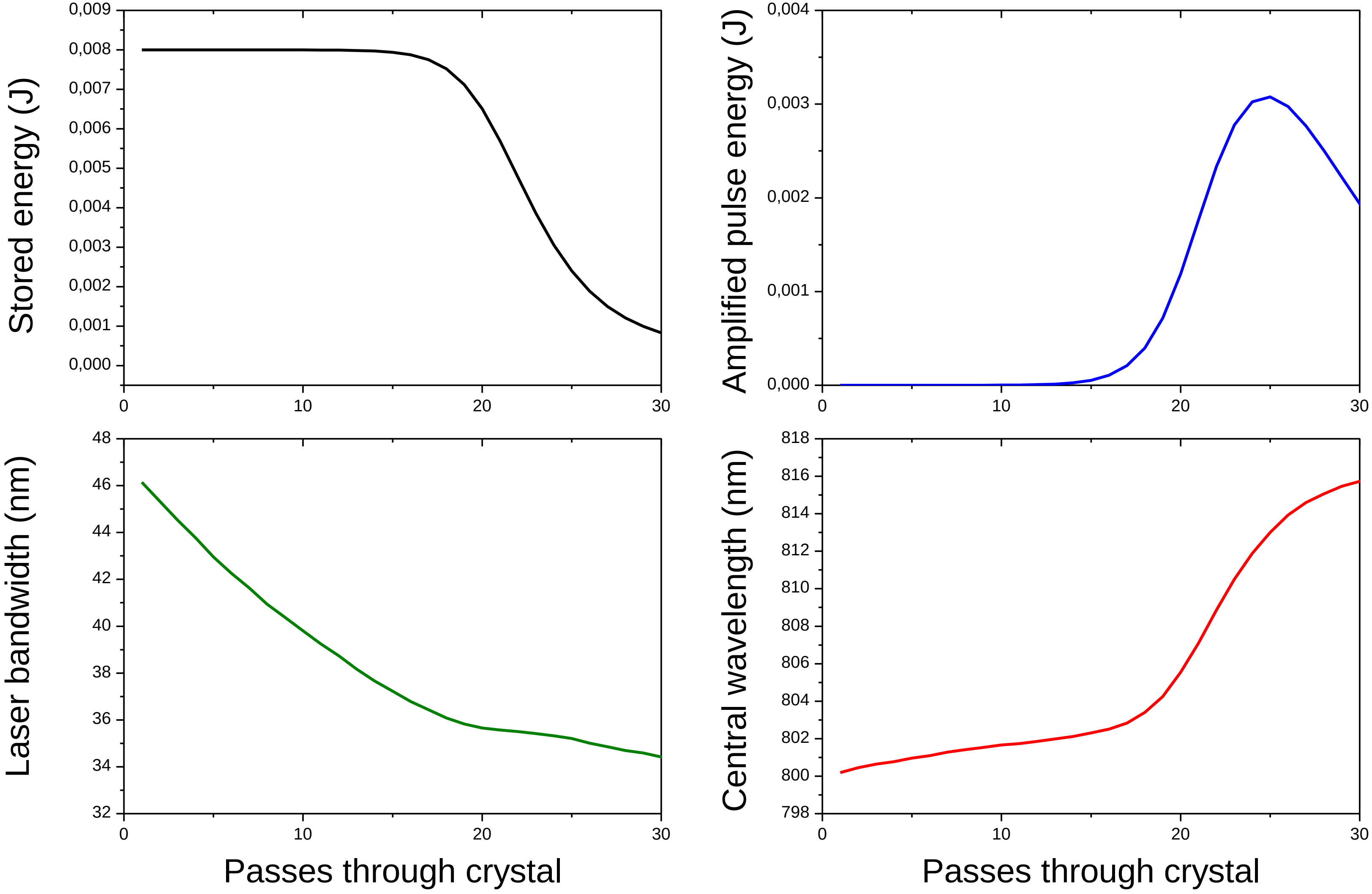
Numerical example

We start at low energy, gain is high, but low extraction efficiency so we need several passes to extract the stored energy



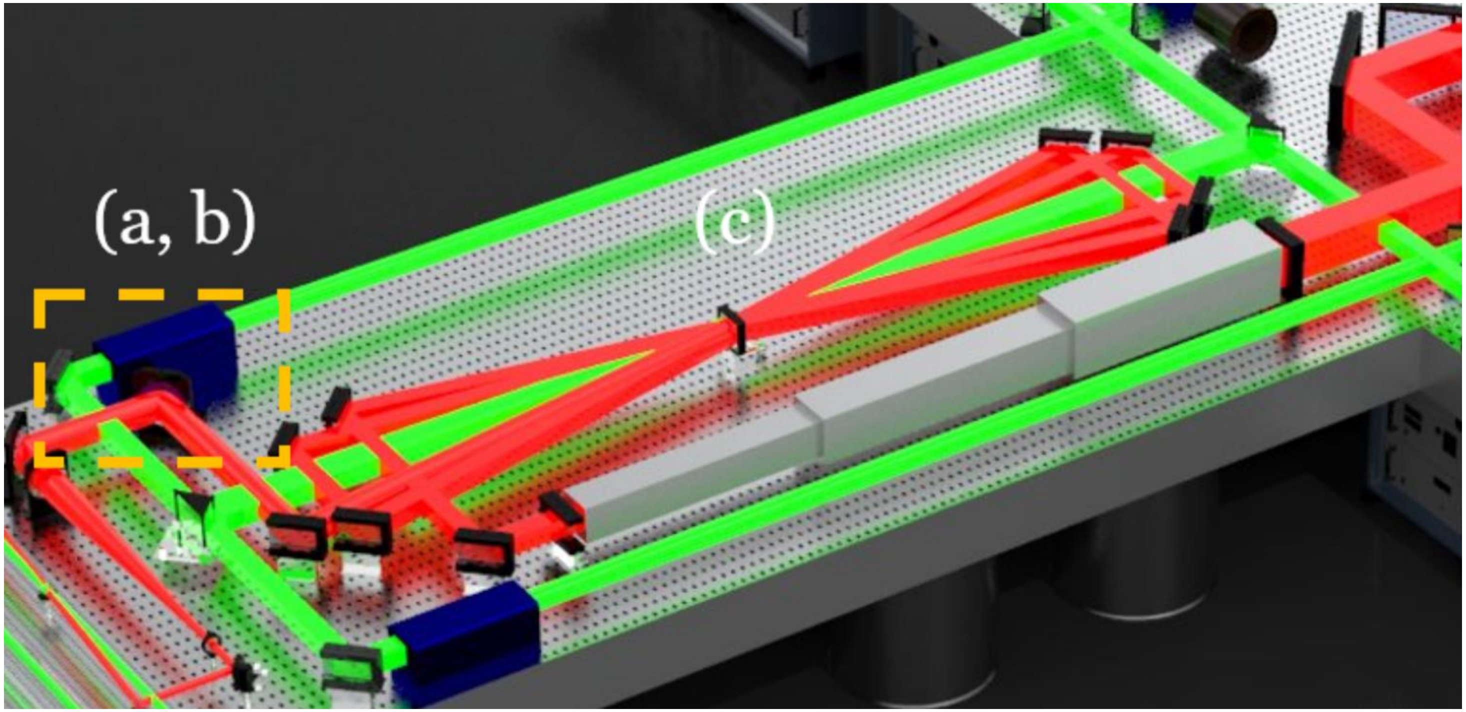
Numerical example

Bandwidth decreases as pulse energy grows: Bad for stretched AND compressed pulses!



Amplifier architecture

Multipass amplifier



Pumped with ns pulses at 532 nm (second harmonic of Nd:YAG)
Upper level lifetime ≈ 3 μsec

Image from J. Jeong et al., Appl. Sci. 9, 2396 (2019)

Amplifier architecture

Regenerative amplifier: pulses oscillate in the cavity until all the stored energy is extracted

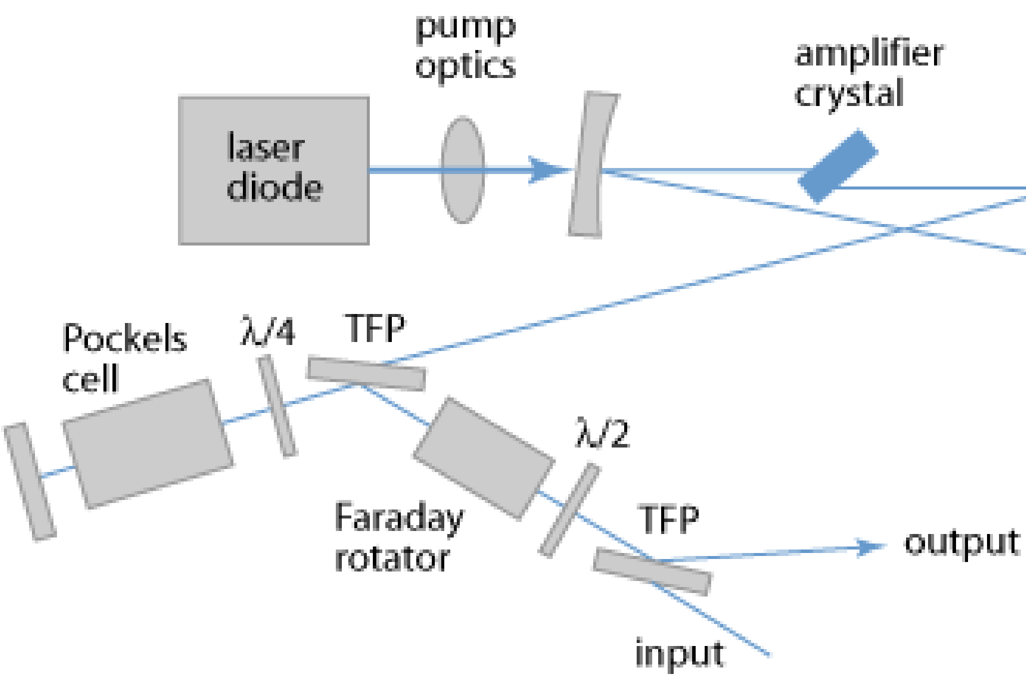


Image from https://www.rp-photonics.com/regenerative_amplifiers.html

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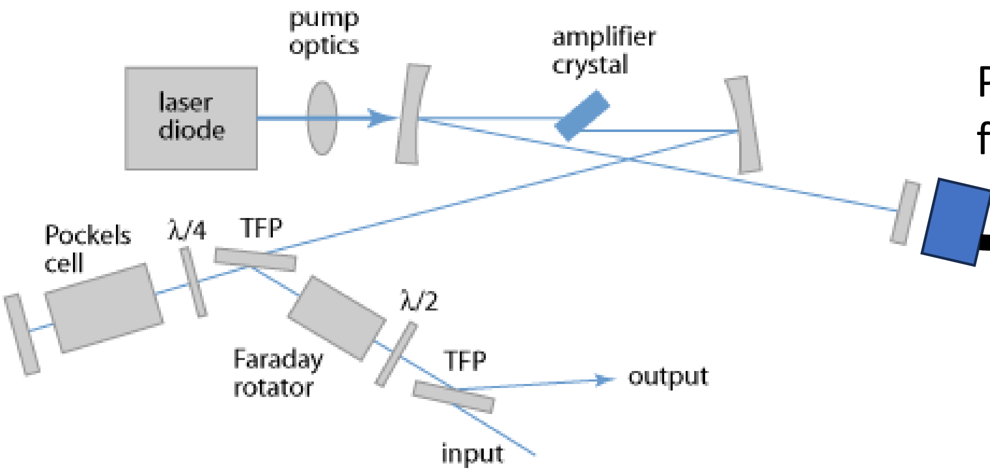
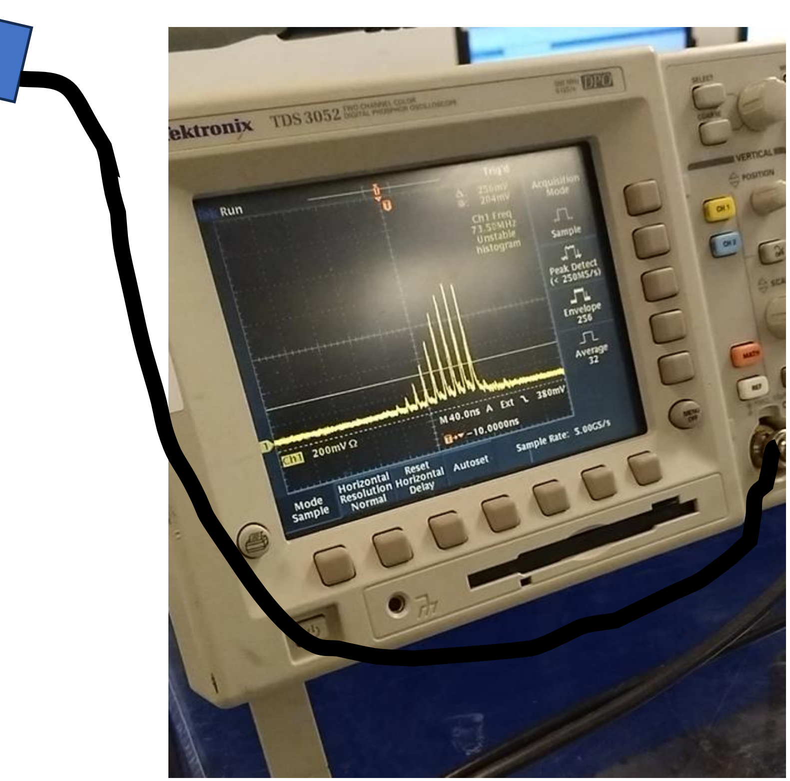


Photodiode looking at leak from the mirror



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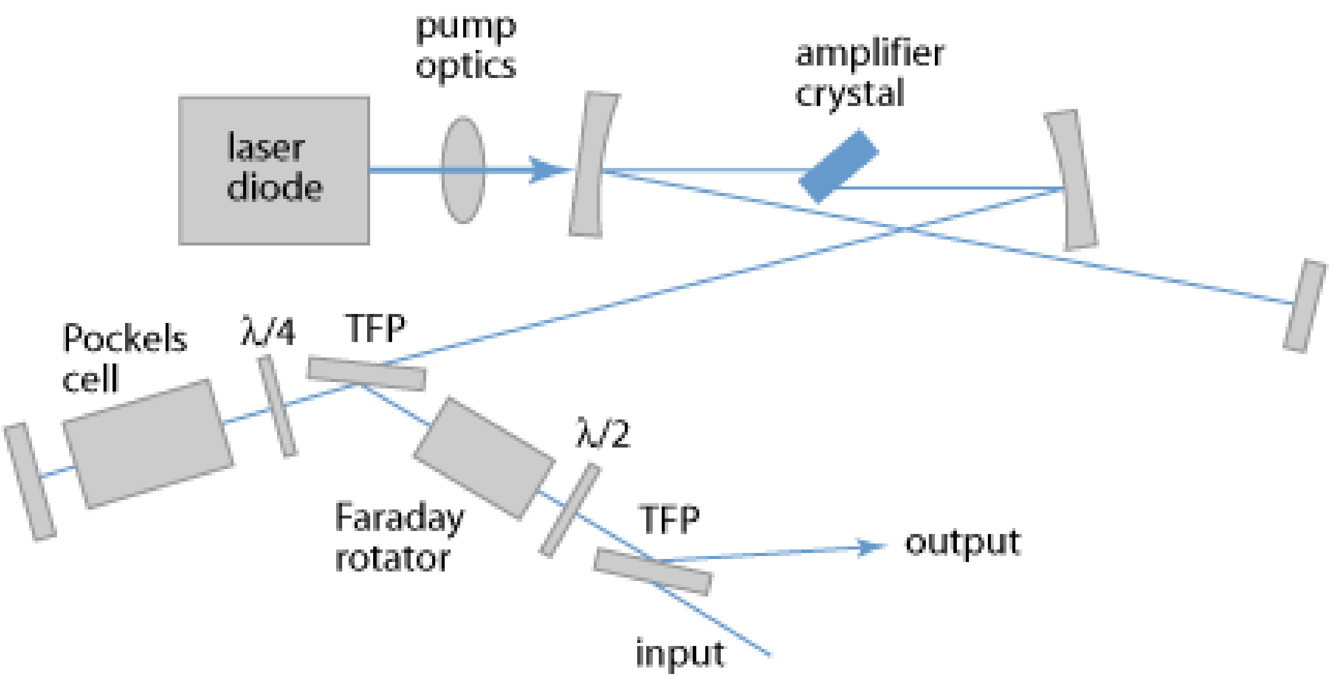
Amplifier architecture

Regenerative amplifier

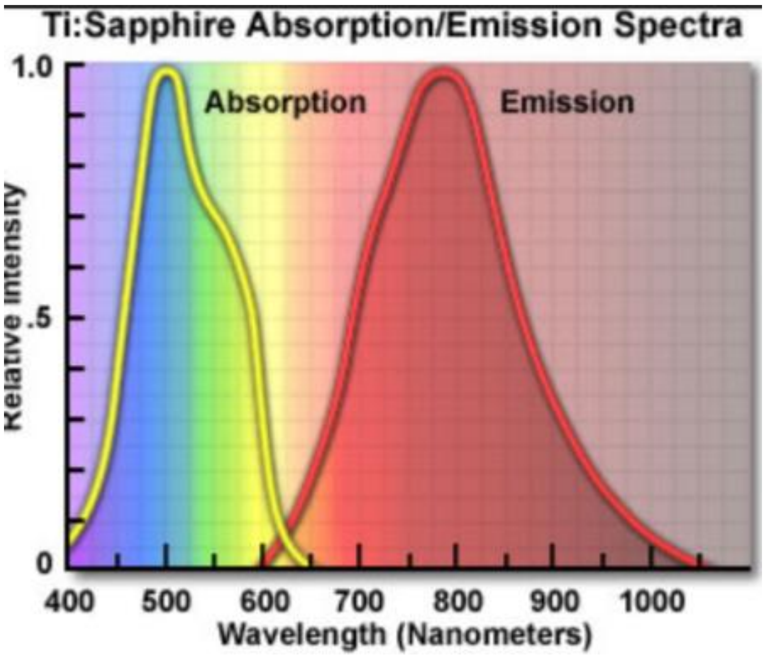


Typically regenerative amplifiers are high gain amplifiers and multipass amplifiers are booster amplifiers

Image from https://www.rp-photonics.com/regenerative_amplifiers.html

Limitations of Ti:Sapphire CPAs

Limitations to spectral range



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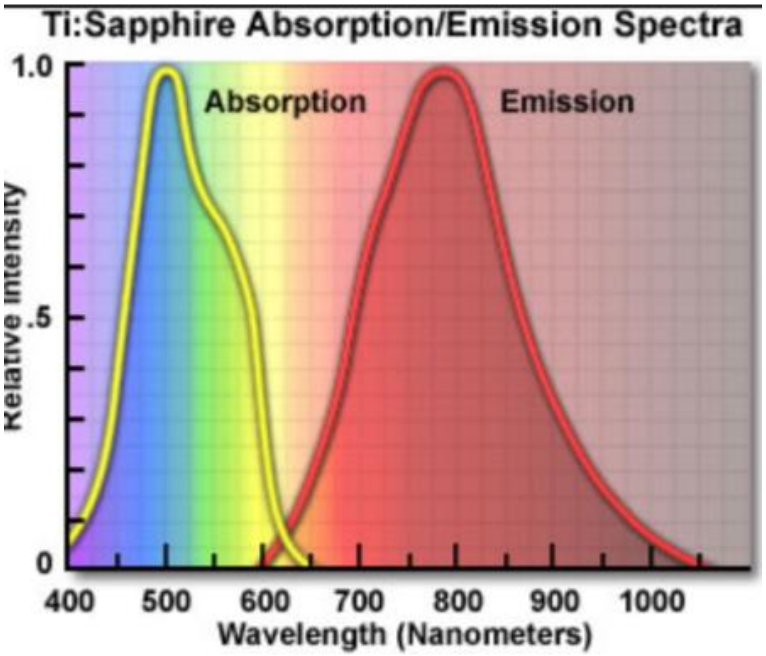

Limitations to pulse duration

gain $\sim e^{g(\omega)L}$

gain narrowing $\Delta\omega_{out} \ll \Delta\omega_{g(\omega)}$

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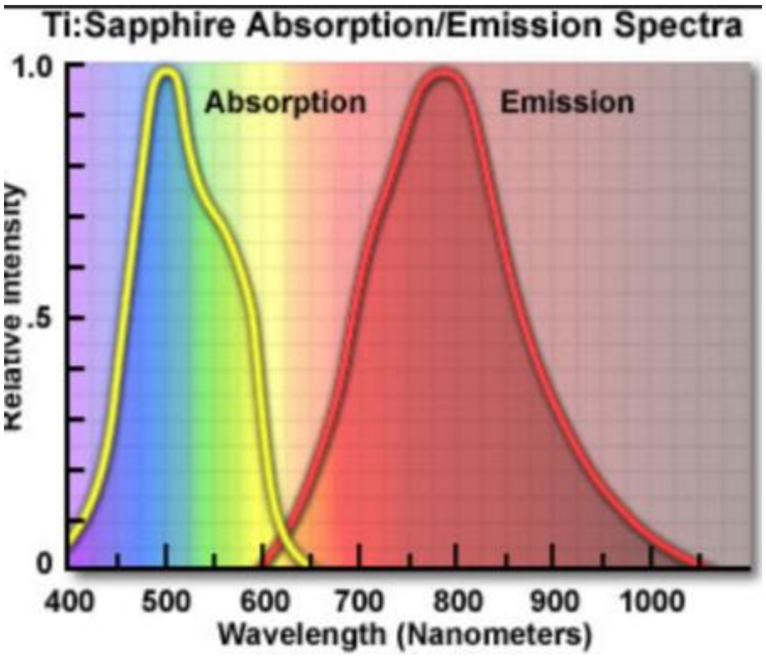

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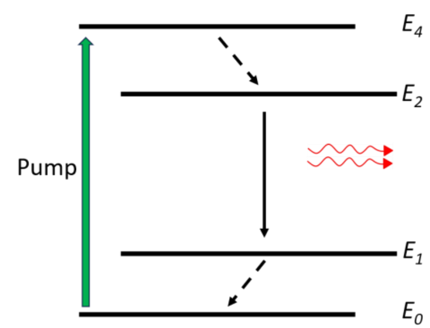
Limitations to power scaling

$$P_{avg} = Energy_{pulse} * f_{rep.rate}$$

Fraction of pump that turns into heat $1 - \frac{\hbar\omega_{laser}}{\hbar\omega_{pump}}$



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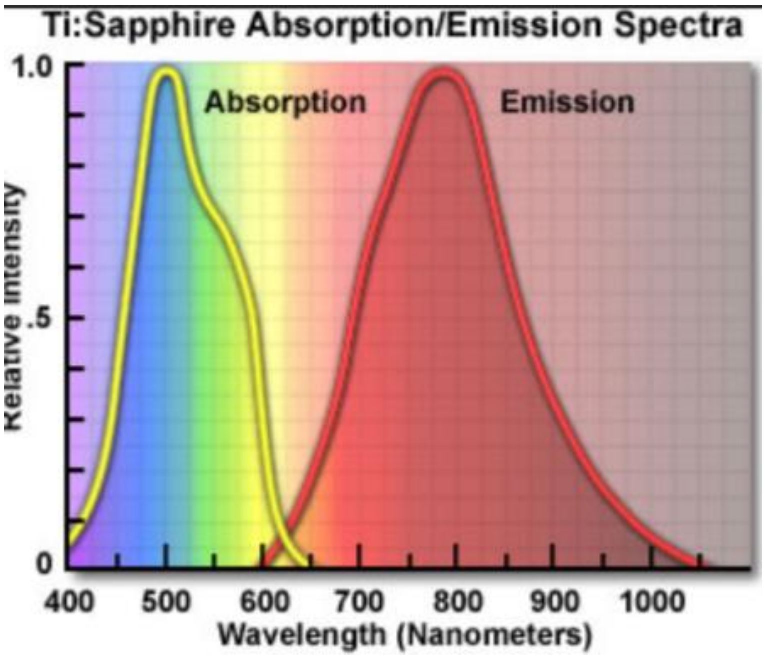
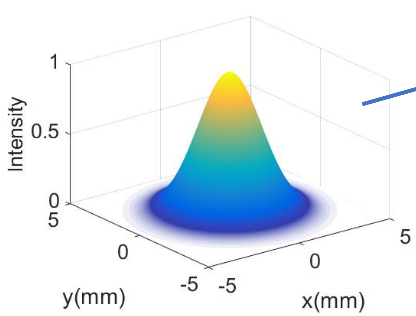


$$P_{pump}(x,y) \propto e^{-2(x^2+y^2)/w^2}$$



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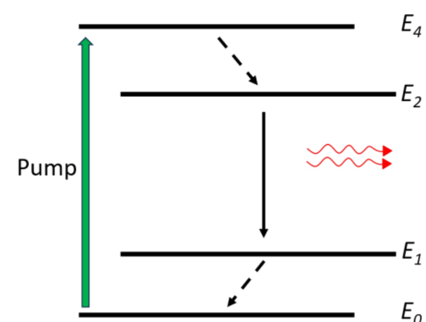
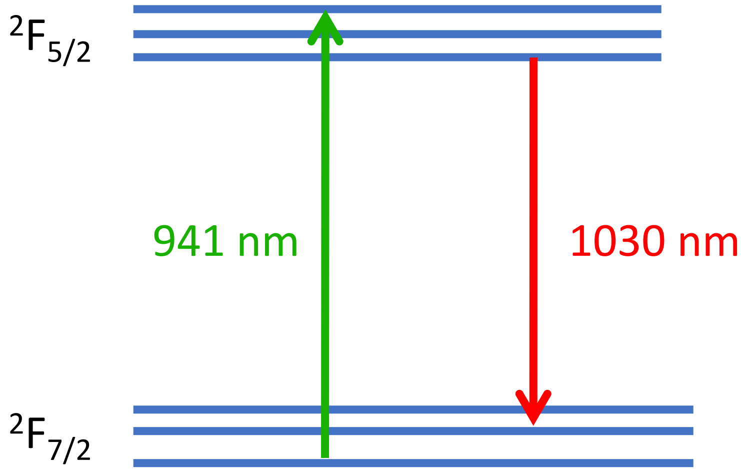


Heat source profile: may originate

- Thermal lensing (dn/dT)
- Thermal induced birefringence
- Damage of material

A laser material for high average power

Yb-doped Yttrium
Aluminum Garnet
Yb:YAG



- Absorption band at InGaAs wavelengths
  - High power laser diodes are commercially available
- Low quantum defect ($1 - \frac{\hbar\omega_{laser}}{\hbar\omega_{pump}} < 0.1$)
  - Potential for high average power operation
- Long upper level lifetime (~1 msec)
  - Efficiently store energy from low peak power pump
- High quality (large) crystals
  - Crystalline or ceramic form

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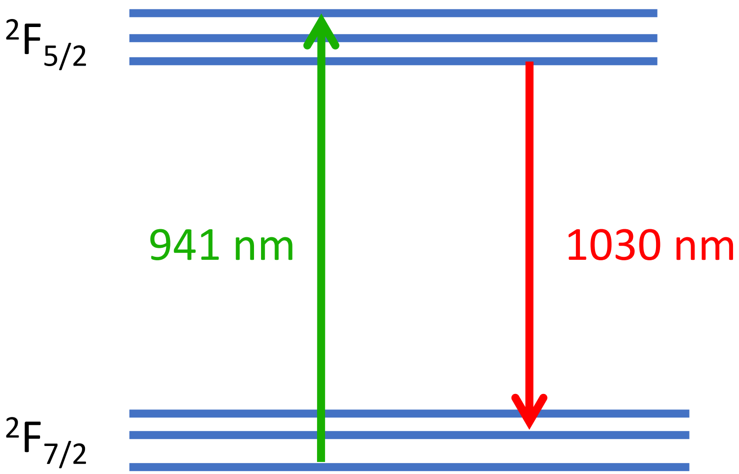

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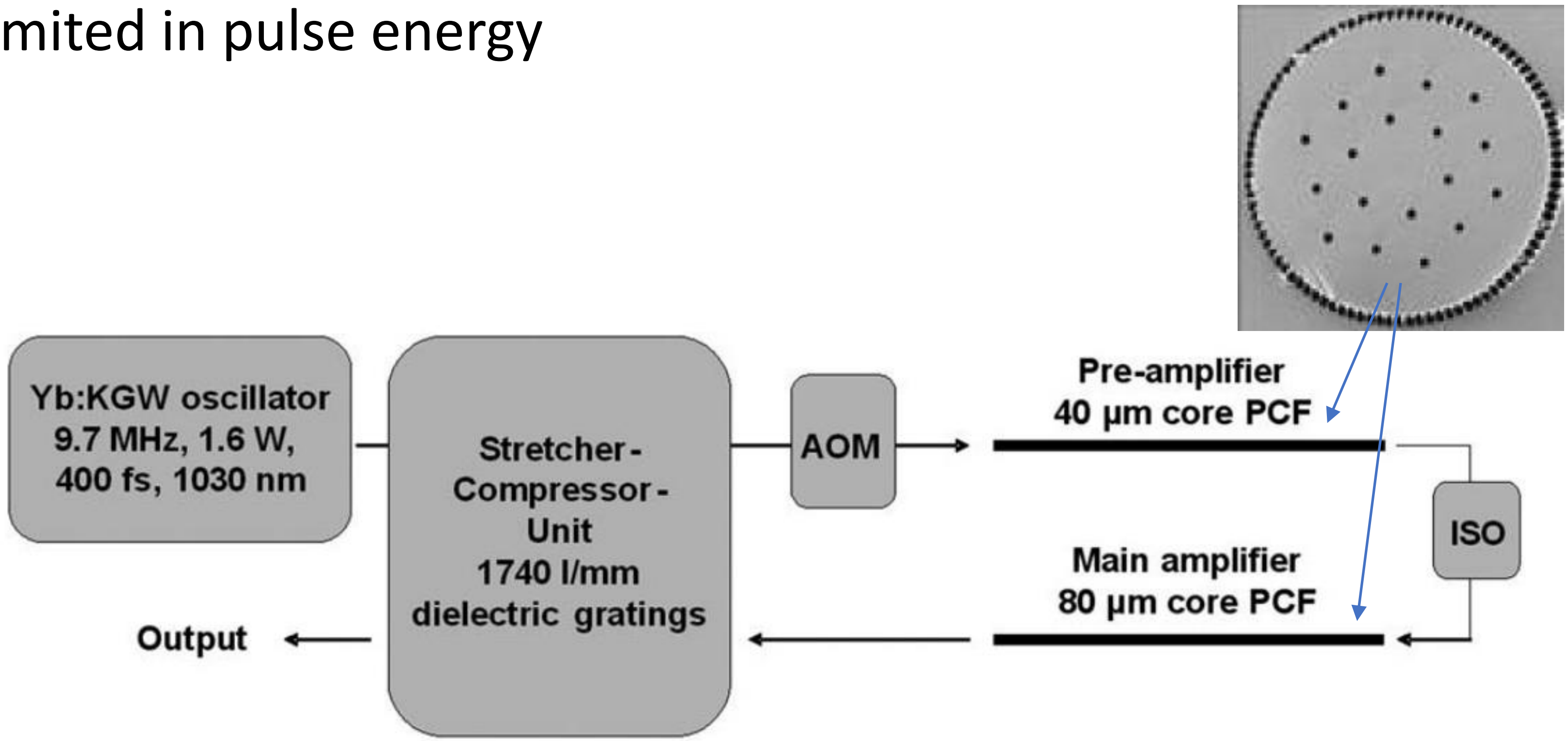
- High quality (large) crystals
  - Crystalline or ceramic form
- BUT narrow gain bandwidth: post-compression, OPCPAs

Architectures for high power operation

Fiber or rod-type amplifiers:

- Heat distributed over large area (can deliver 100s of W)
- Excellent beam quality (when multi-mode operation is suppressed)
- Limited in pulse energy



Röser, et al., Opt. Lett. 32, 3495 (2007)

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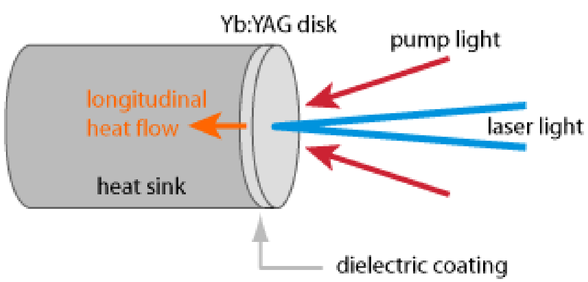
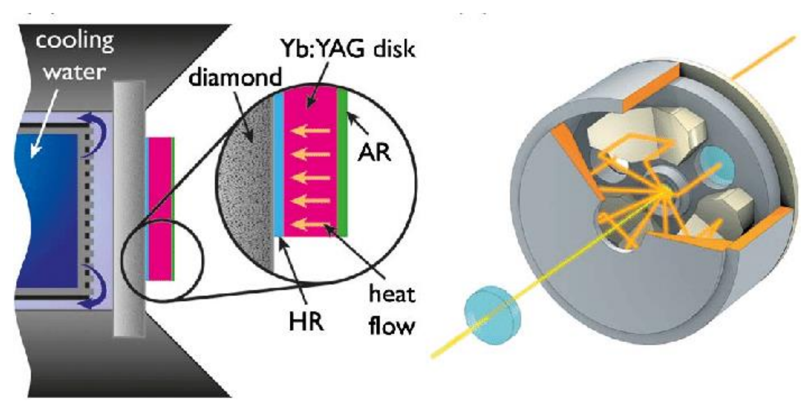
Thin-disk amplifiers (typically Yb:YAG):

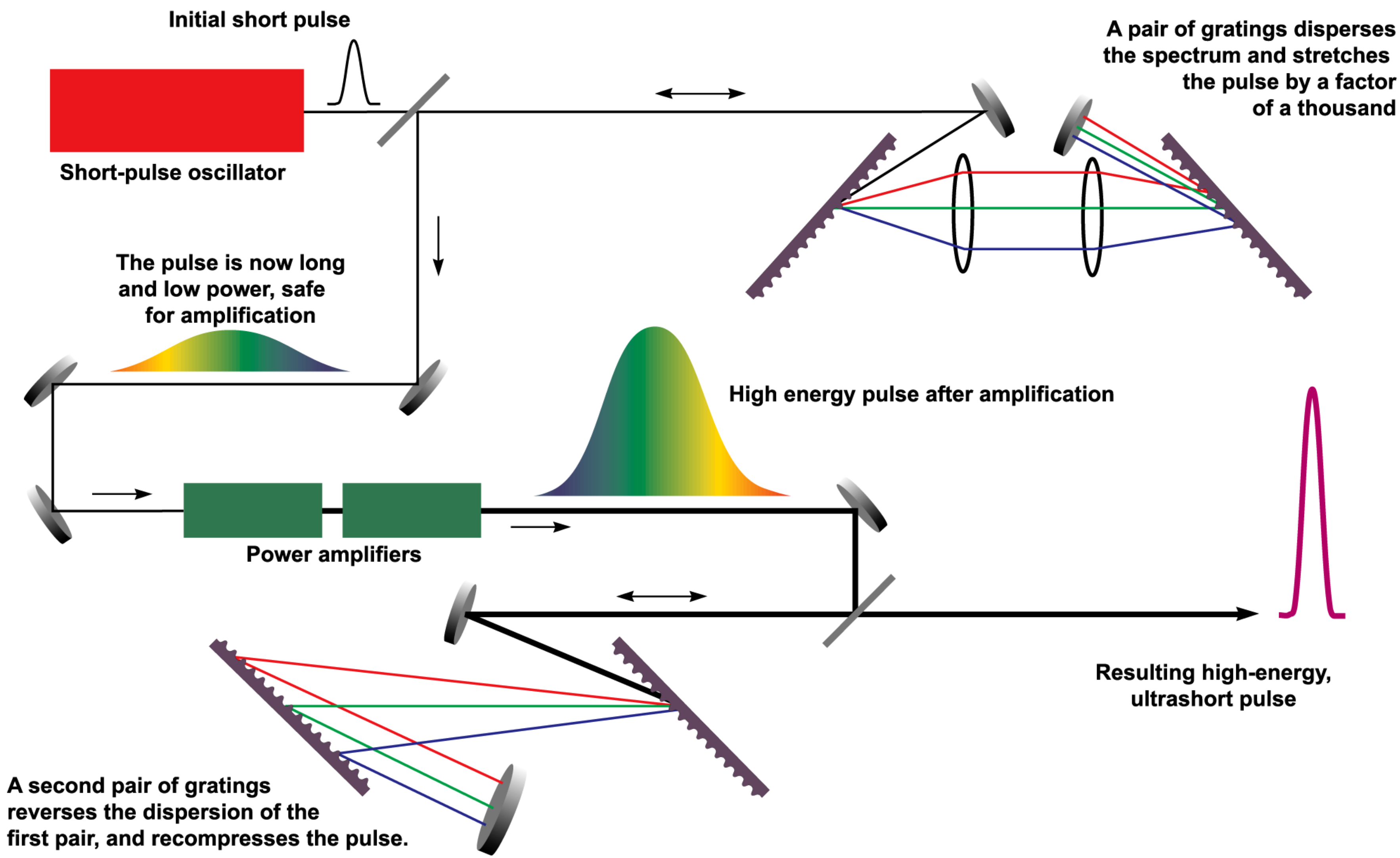
- Longitudinal heat flow (minimized thermal lensing)
- Compatible with higher pulse energy
- Longer pulses than Yb-doped fibers





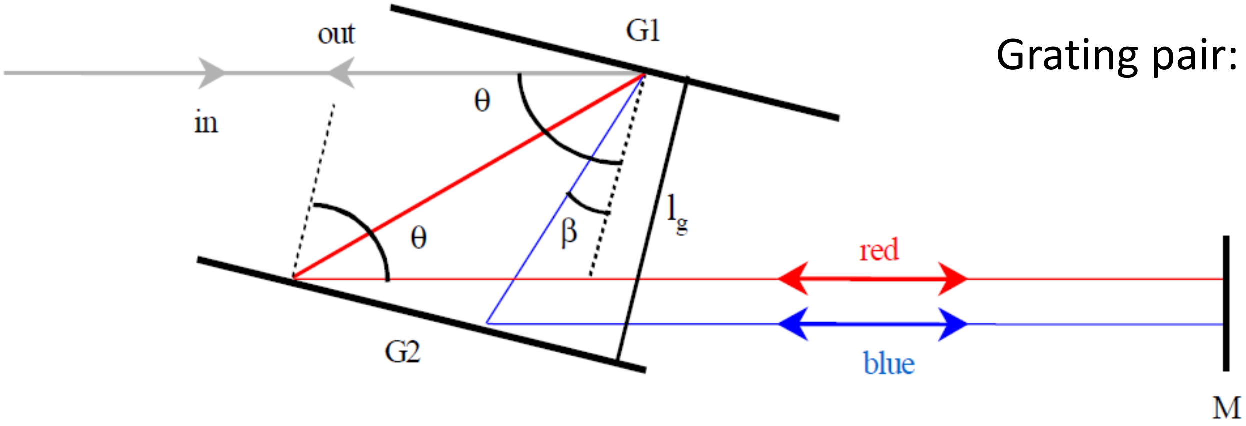
Fattahi et al., Optica 1, 45 (2014)

Stretcher/Compressor



CPA idea was being exploited since 1960 in radar signals

Stretcher/Compressor



Grating pair: $l_{red} > l_{blue}$

In 1969 Treacy described how to exploit angular dispersion to introduce negative GDD using a pair of gratings

Treacy, IEEE JQE 5, 454 (1969)

Stretcher/Compressor

In 1984 O. Martinez introduced the idea of adding a telescope and control the effective distance between the gratings →control sign and magnitude of GDD

$$l_{eff} = [l - 2(f_1 + f_2)](f_1/f_2)^2. \quad (8)$$

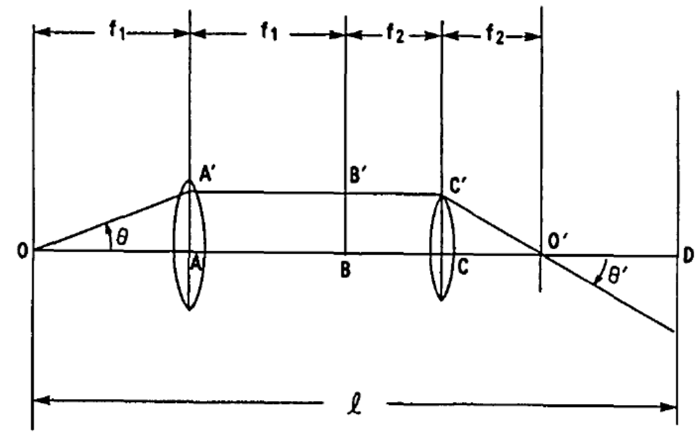
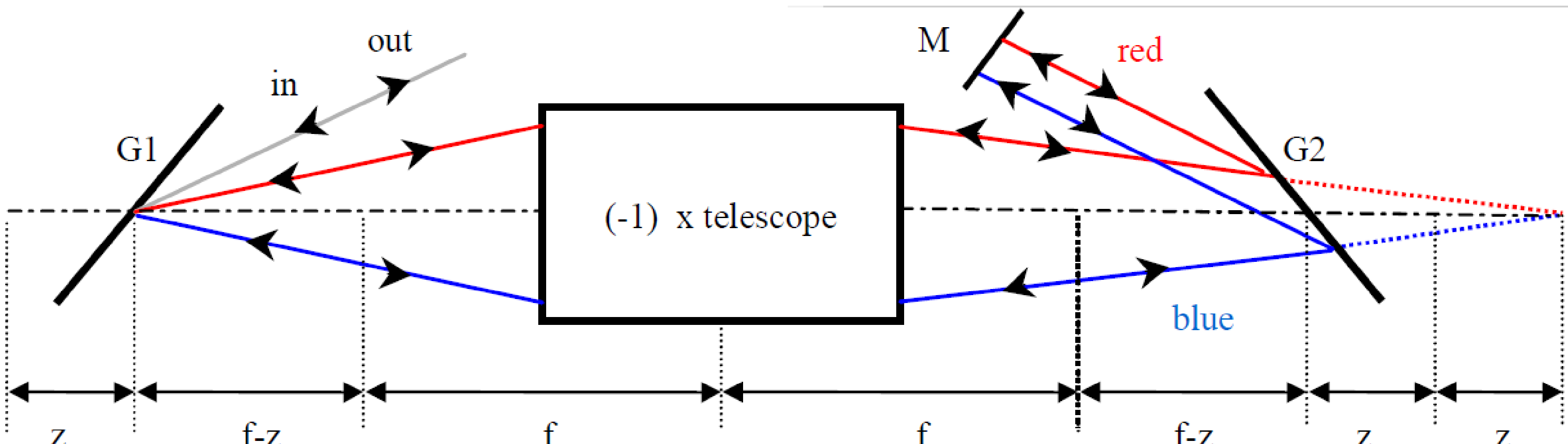


Fig. 2. Effect of a telescope. Here, f_1 and f_2 are the focal distances of the lenses. The distance between O and O′ (focal planes) must be subtracted from P, because the optical paths for waves propagating at different angles are identical. The increase in the angular dispersion can, however, usually overcome this disadvantage.

Grating pair + telescope: $l_{red} < l_{blue}$



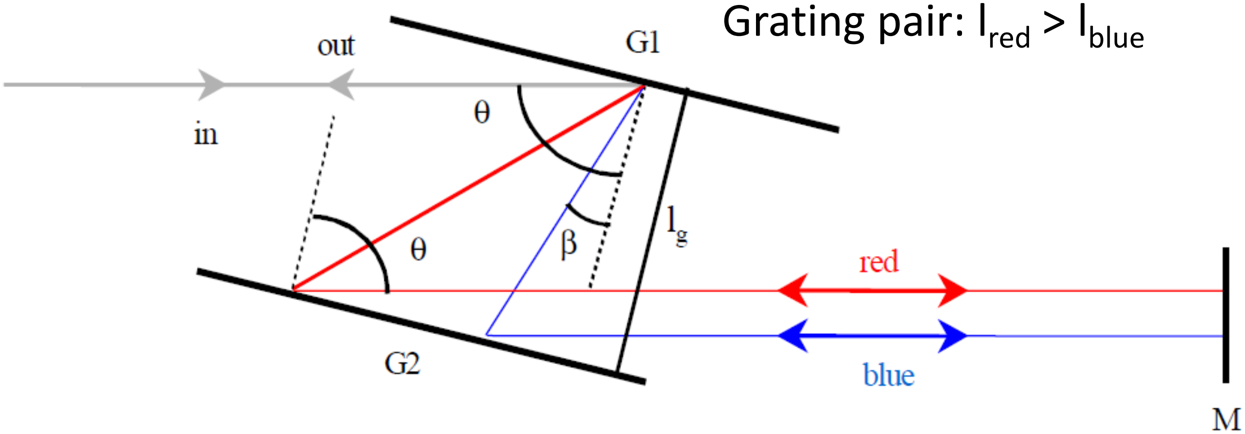
Martinez et al., JOSA 1, 1003 (1984)

Stretcher/Compressor

Degrees of freedom in amplifier dispersion management:

- Incidence angles on gratings and separation between gratings: GDD and TOD control

Grating pair: $l_{red} > l_{blue}$



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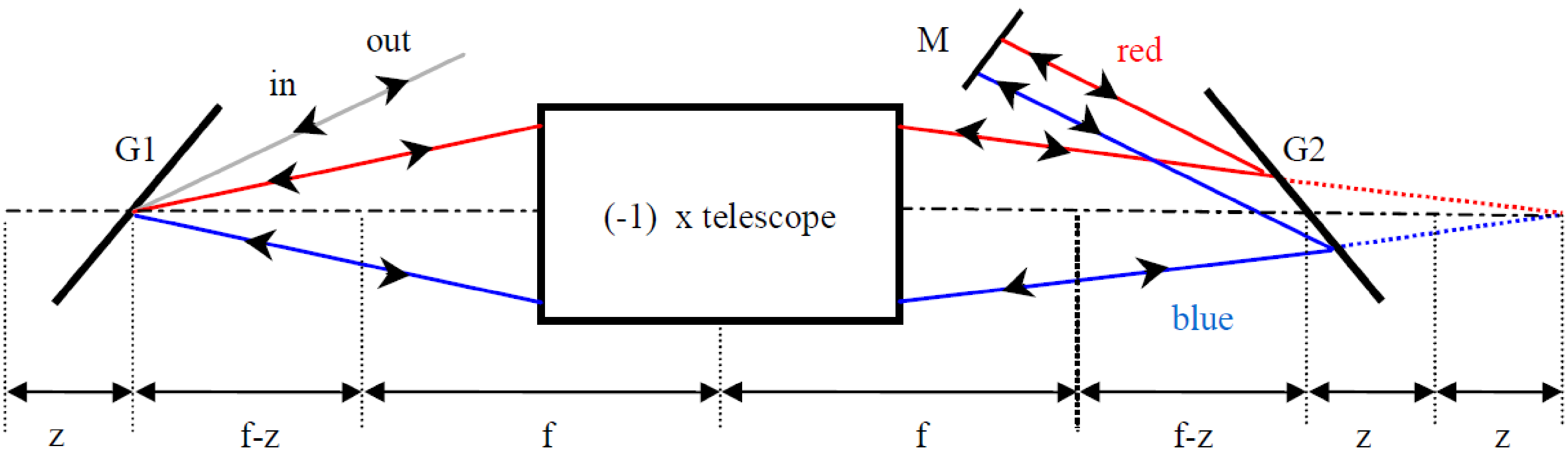
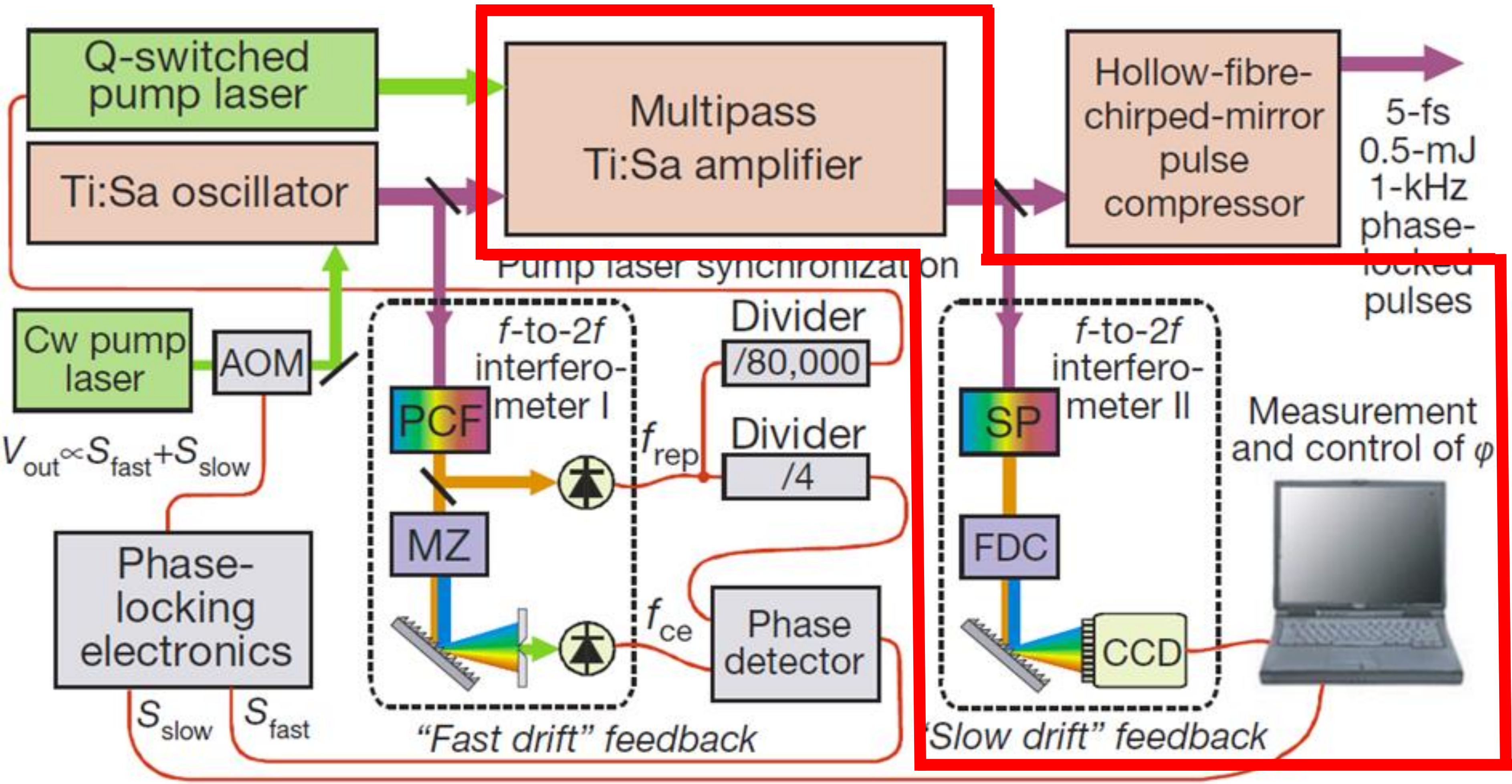


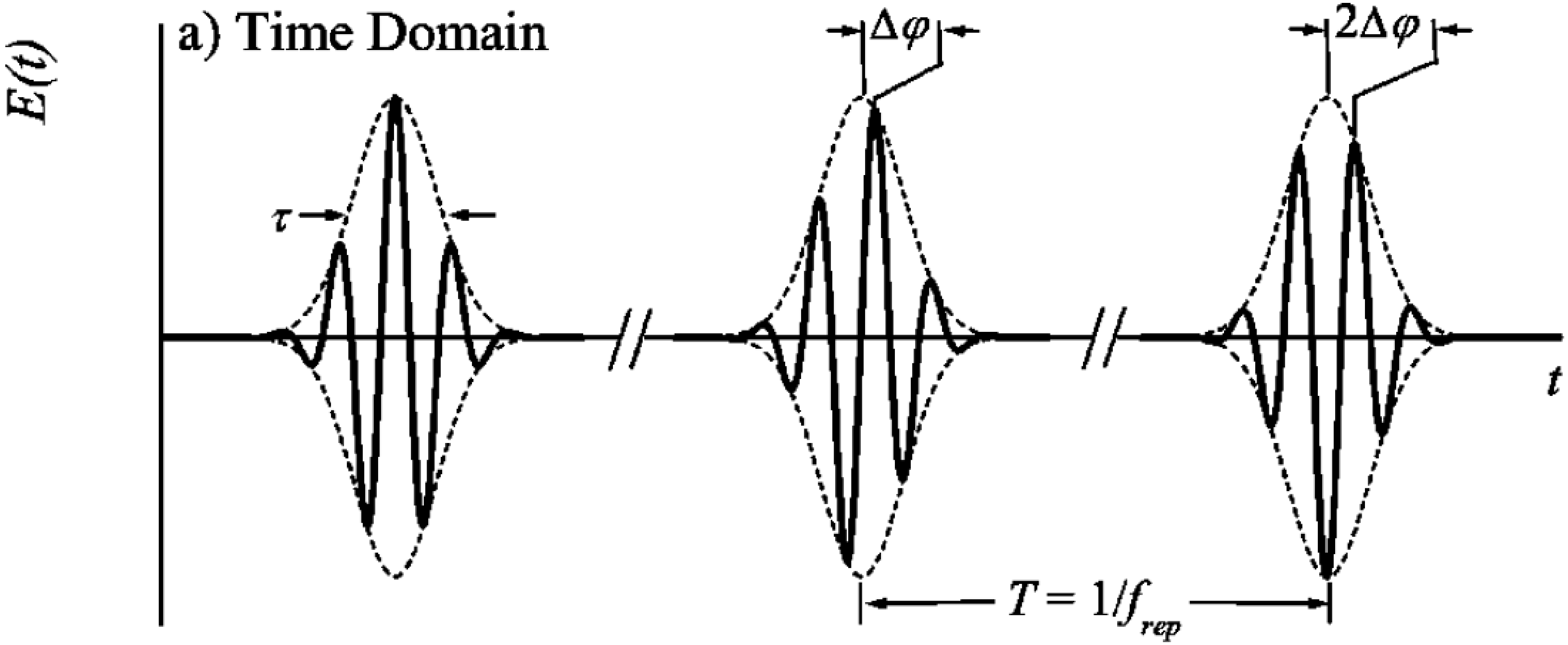
A state-of-the-art laser system for attosecond science



A. Baltuska et al., Nature 421, 611 (2003)

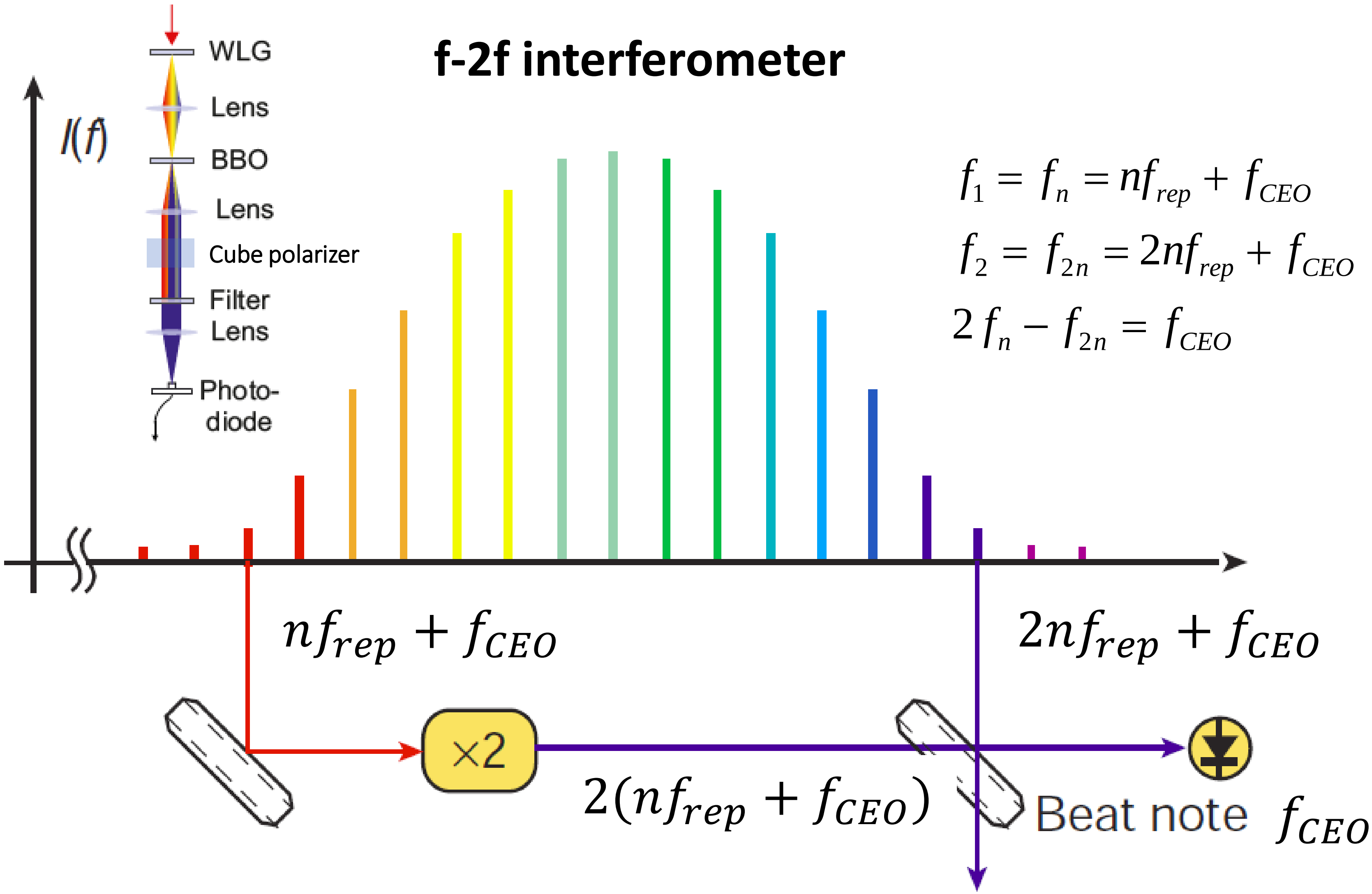
How to measure/control the CEP

In the oscillator…



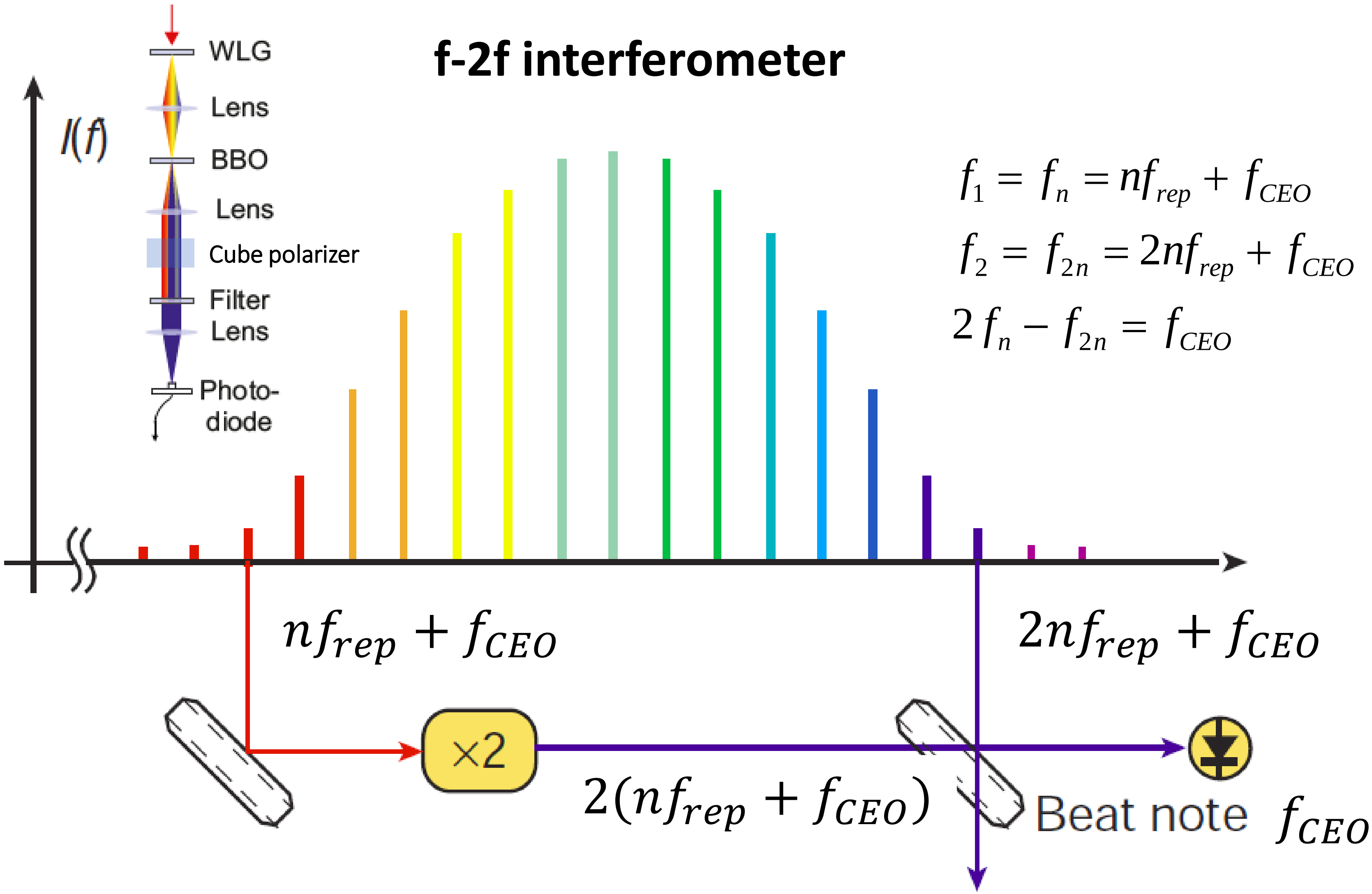
We measured and stabilized f_{ceo}. **Can we use the same technique after the amplifers?**

How to measure/control the CEP



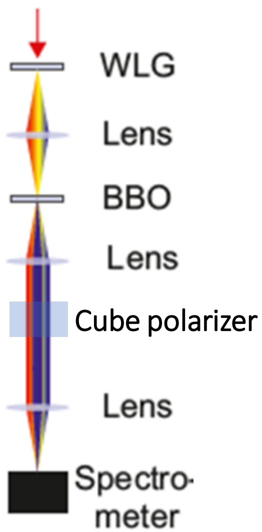
We measured and stabilized f_{ceo}. **Can we use the same technique after the amplifers?**

How to measure/control the CEP



We measured and stabilized f_{ceo}. **Can we use the same technique after the amplifers? NO. f_{CEO} should be zero for the amplified pulses**

How to measure/control the CEP



f-2f interferometer

Kakehata et al., Opt. Lett. 26, 1436 (2001)

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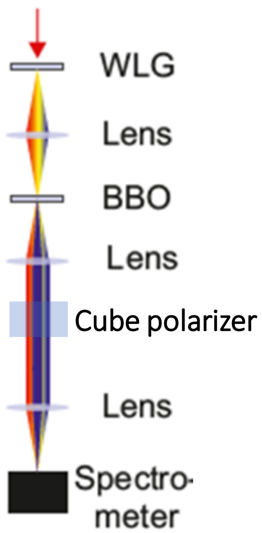

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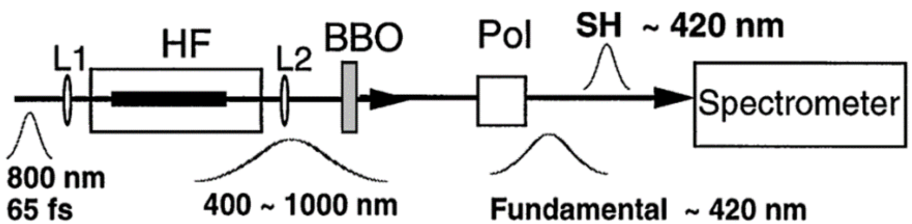

Kakehata et al., Opt. Lett. 26, 1436 (2001)

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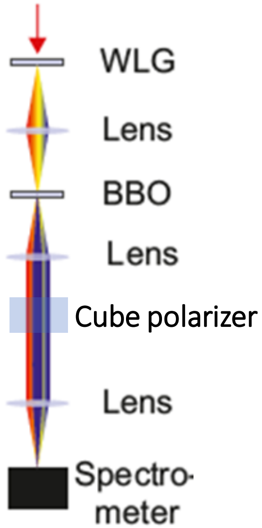

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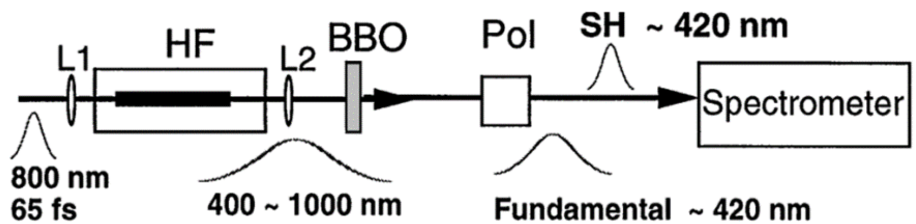

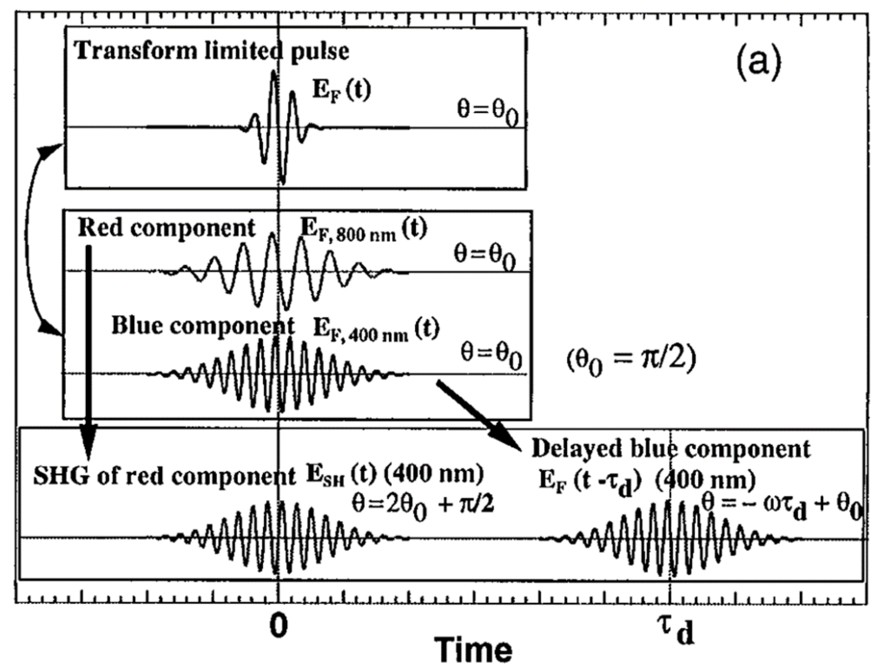

Kakehata et al., Opt. Lett. 26, 1436 (2001)

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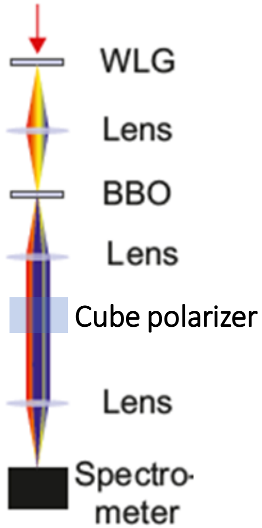

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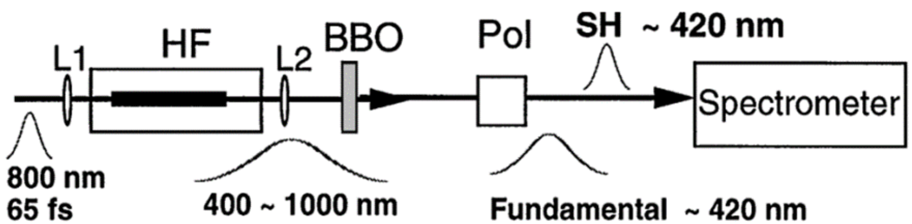

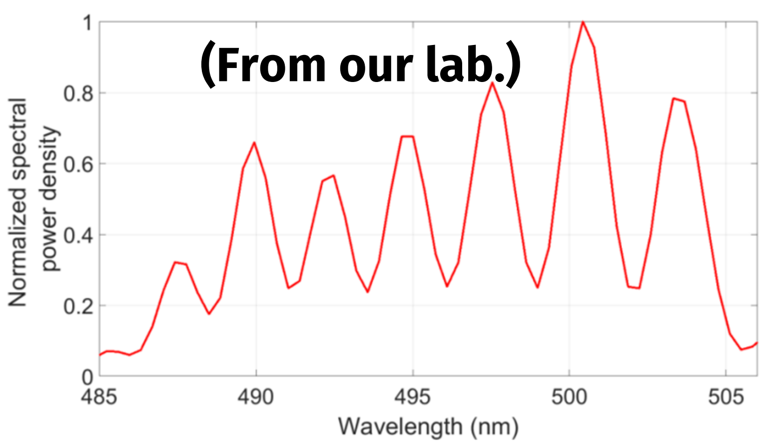

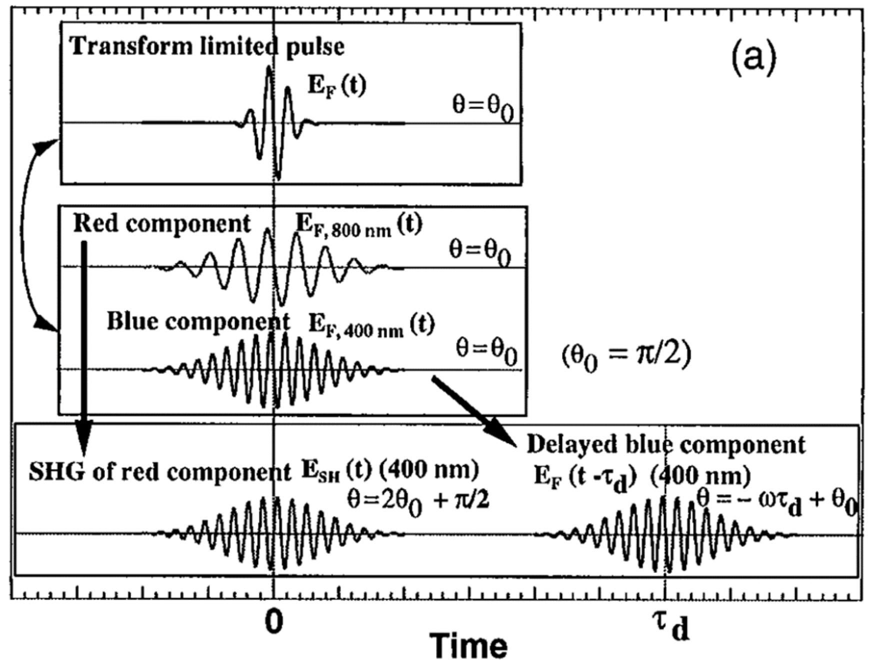

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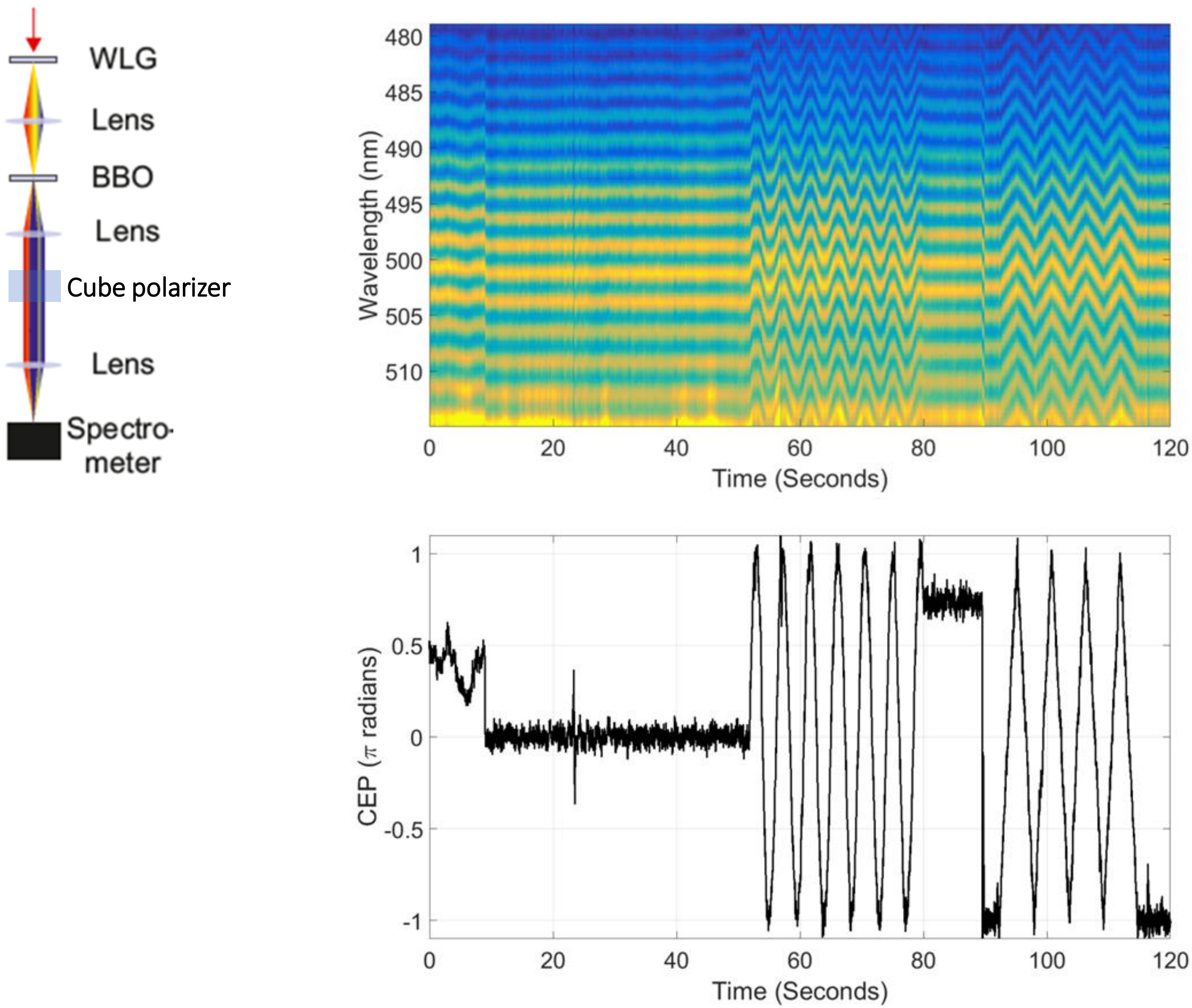

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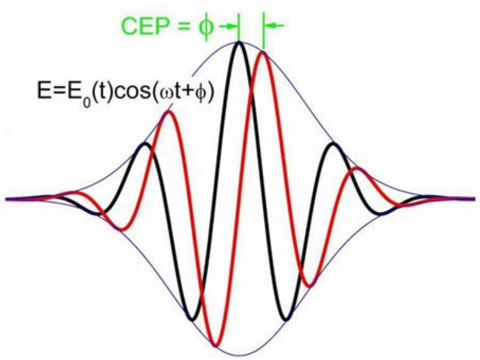
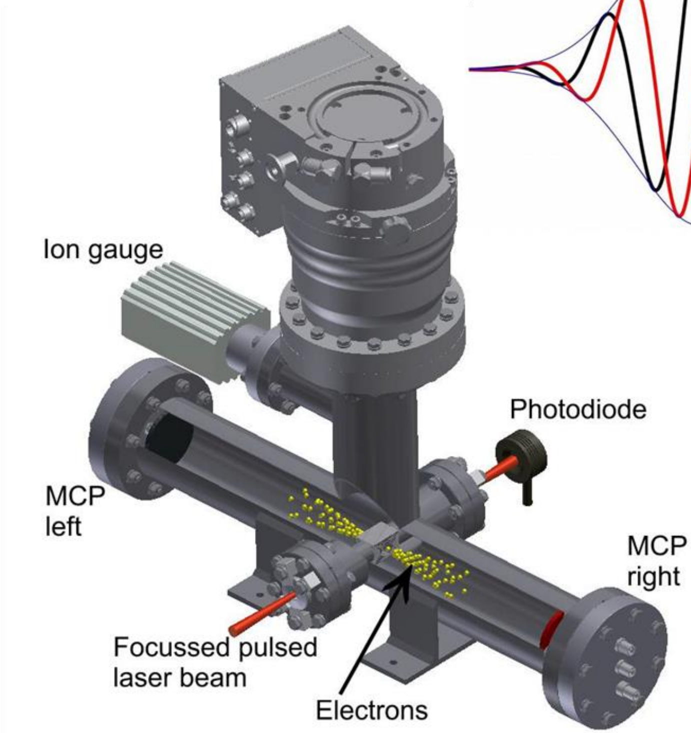
Absolute measurement of CEP

Stereo Above-Threshold Ionization





W. Becker et al., Adv. At. Mol. Opt. Phys. 48, 35 (2002)
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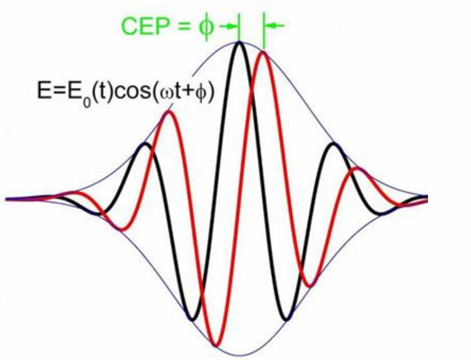
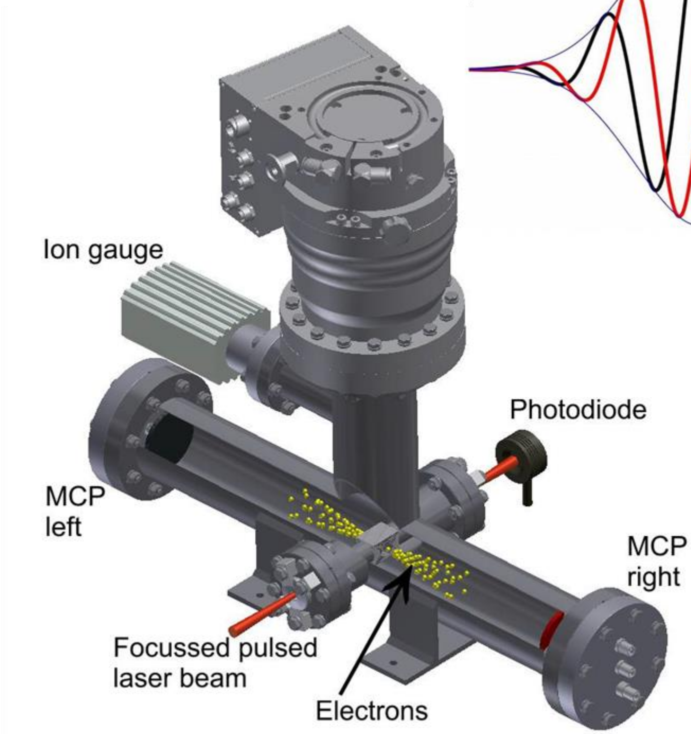
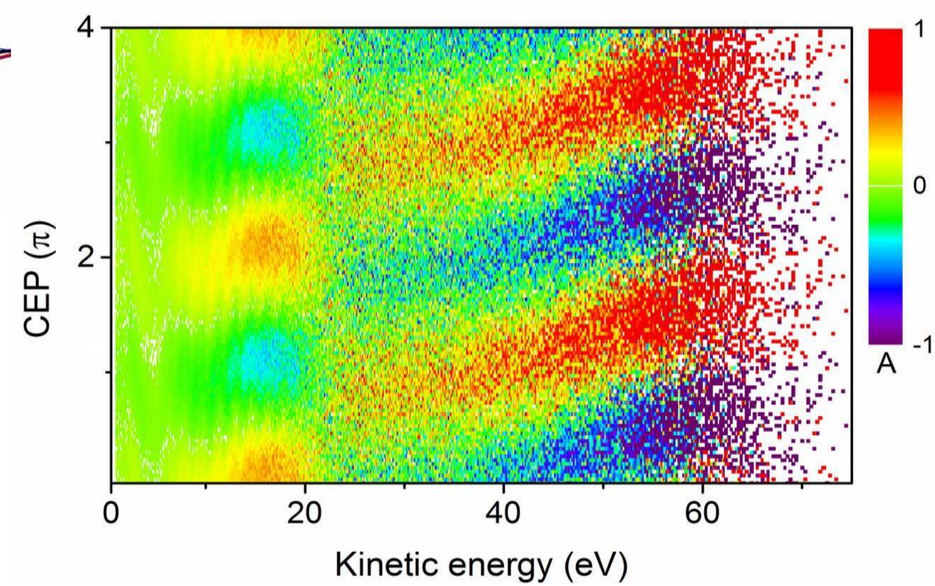




$$Asymmetry(KE) = \frac{N_R(KE) - N_L(KE)}{N_R(KE) - N_L(KE)}$$



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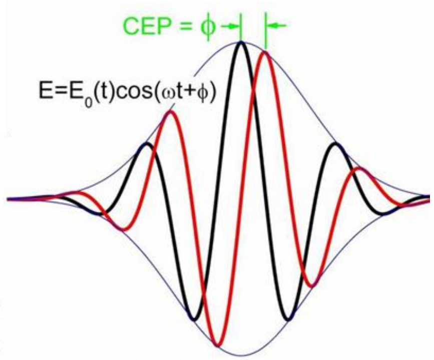

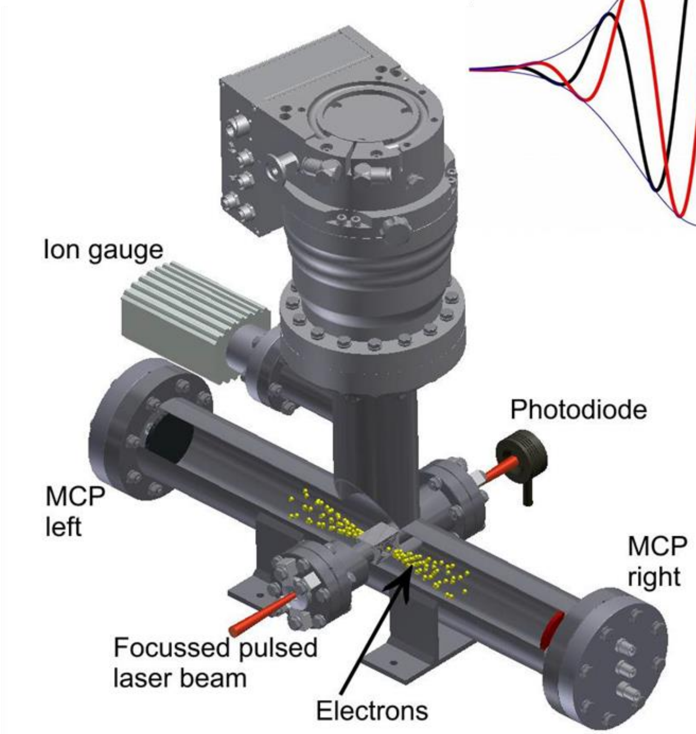

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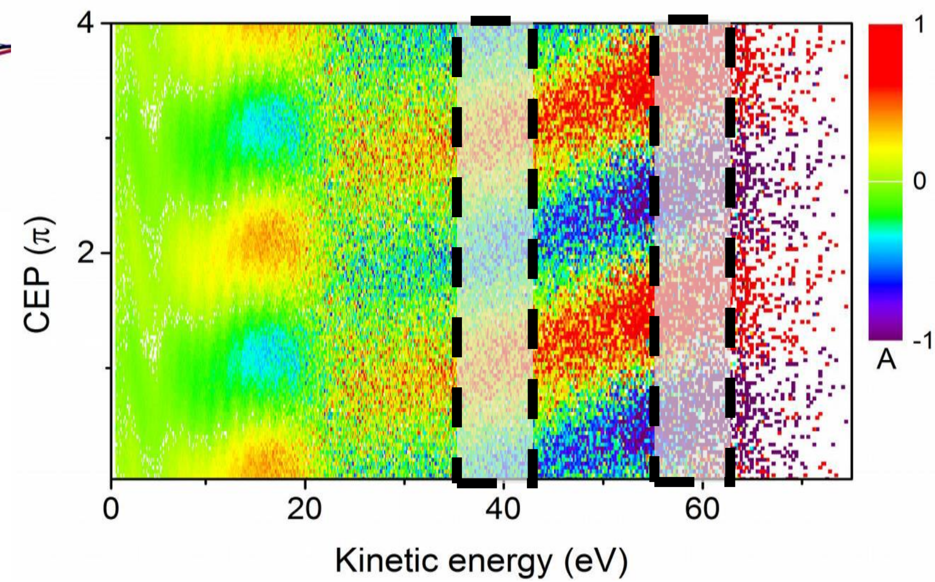

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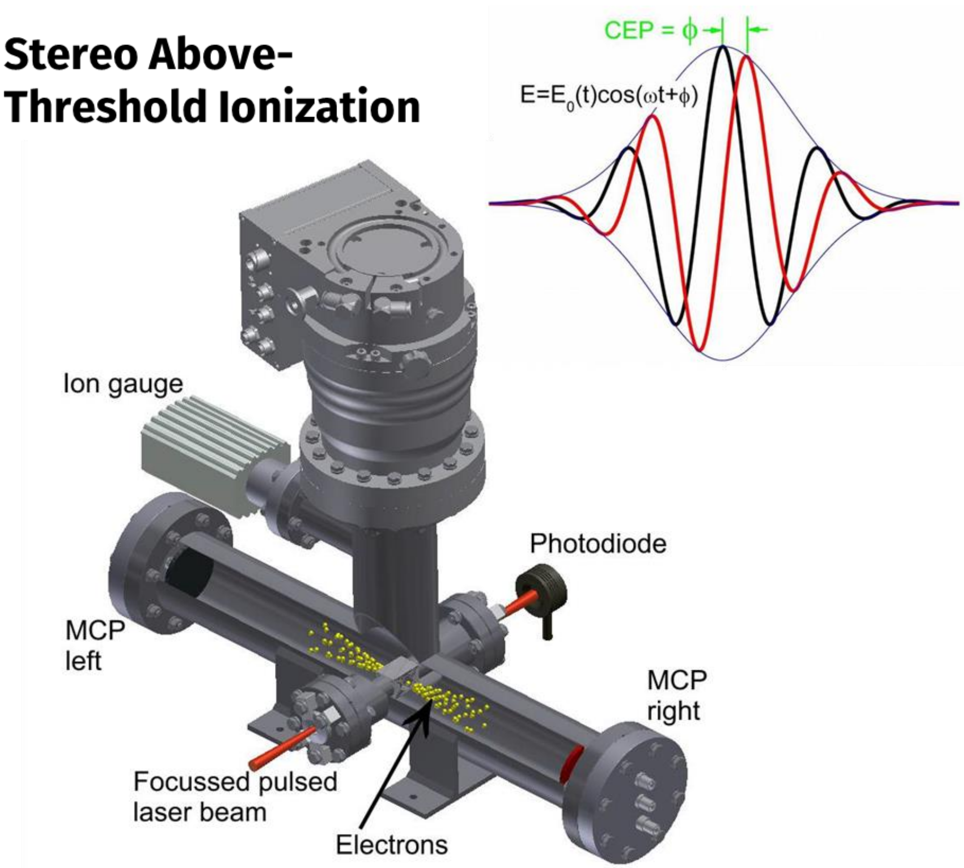

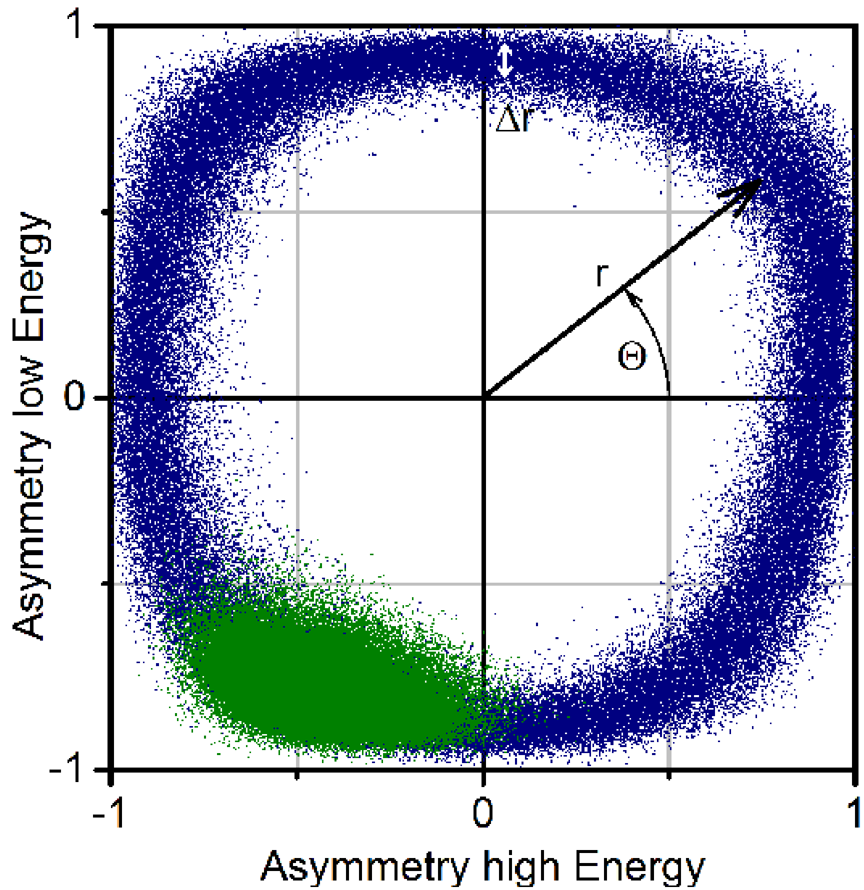

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W. Becker et al., Adv. At. Mol. Opt. Phys. 48, 35 (2002)
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Useful materials for further reading:

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W. Koechner, Solid State Laser Engineering (Springer Series in Optical Sciences volume 1, Springer New York)

A. Baltuska et al., Nature 421, 611 (2003)

U. Keller, Ultrafast Lasers (Springer 2021)

Wittmann et al., Nat. Phys. 5, 357 (2009)

Kakehata et al., Opt. Lett. 26, 1436 (2001)