Development of Ultrafast and Ultraintense Laser Technology for Attosecond Dynamics and High Field Physics

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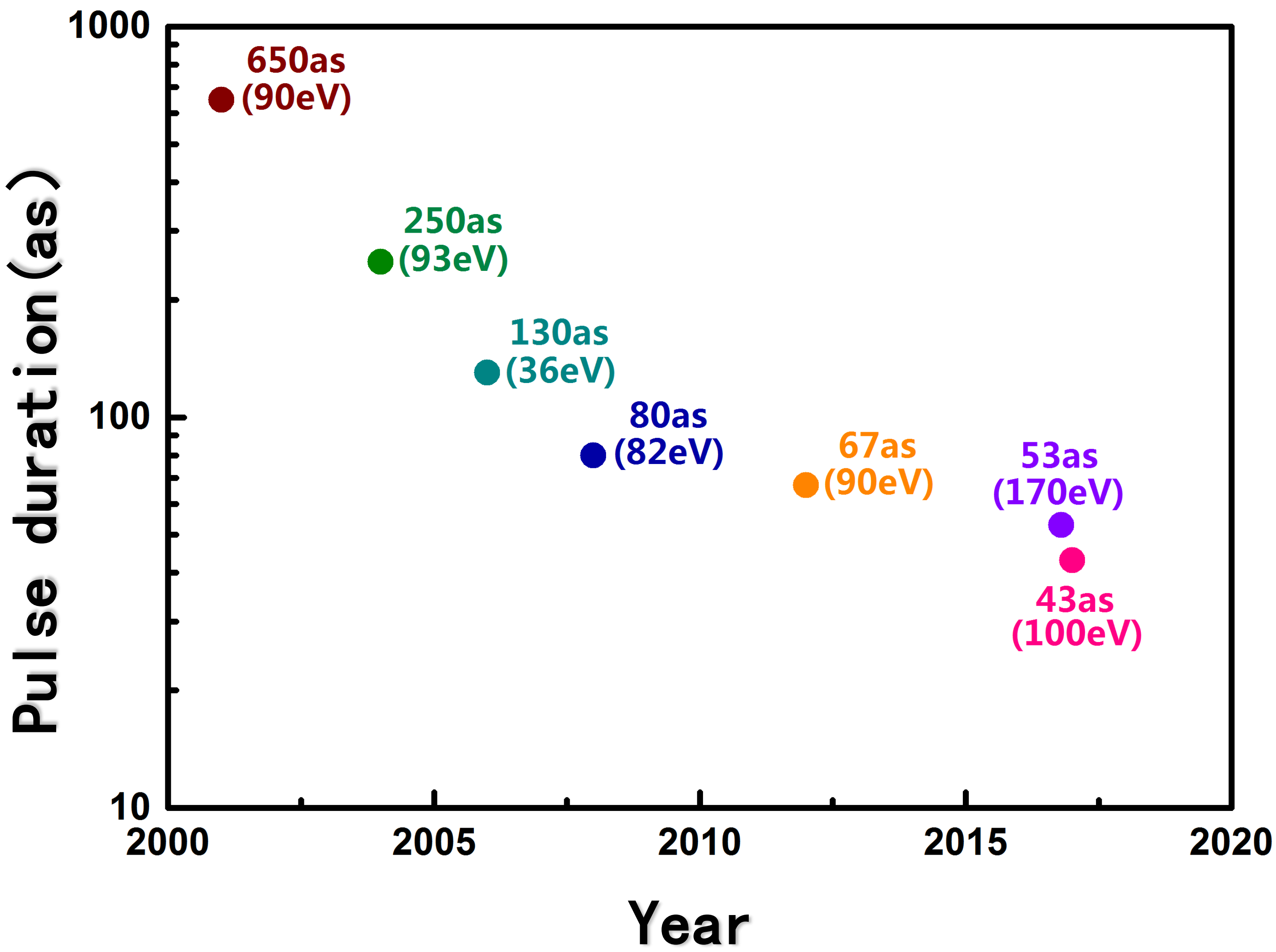
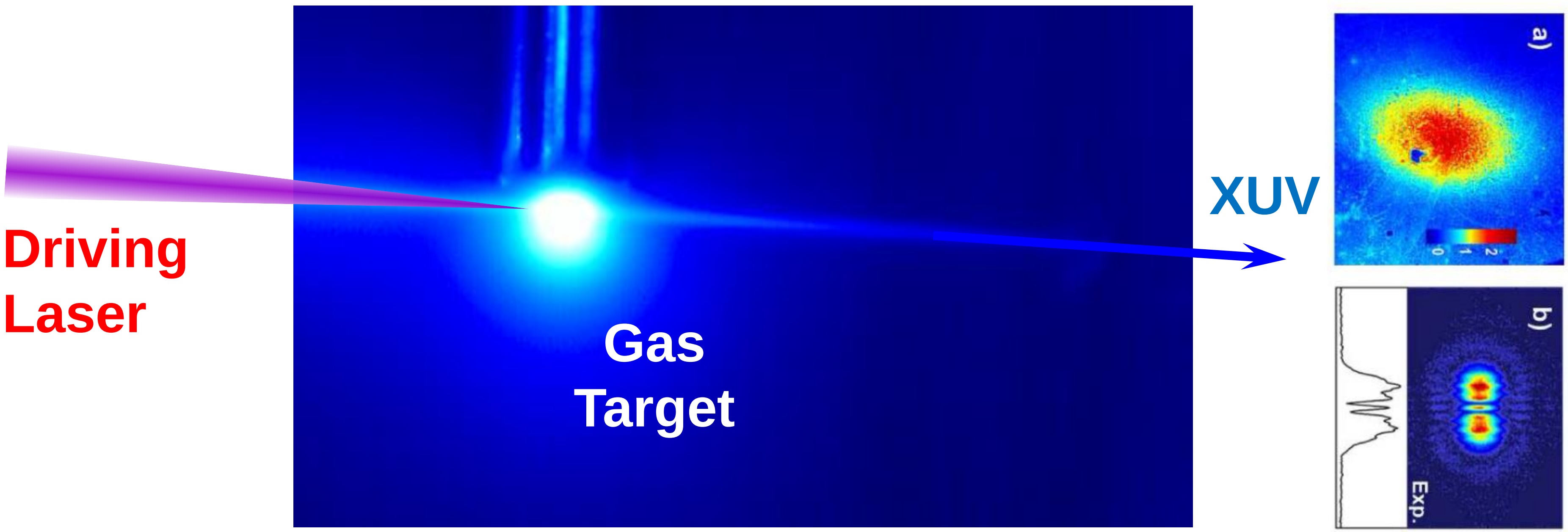
Outline

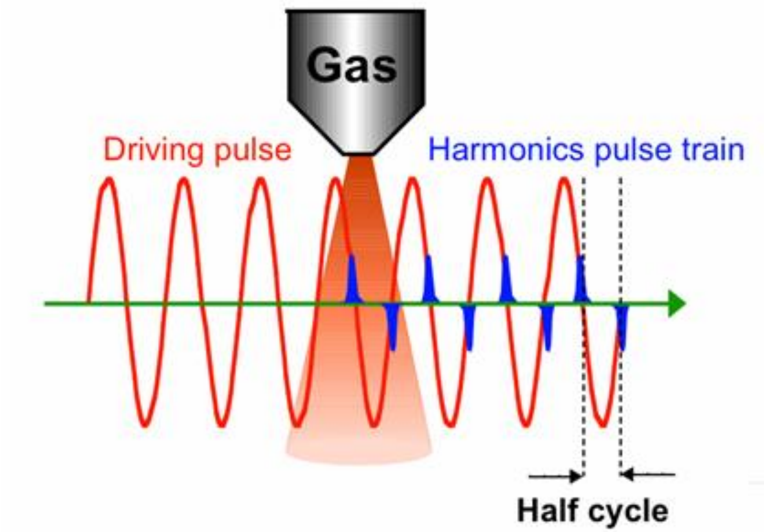
- ➢ **General Introduction**
- ➢ **Ultrahigh Intensity Laser-Toward multi-PW power**
  - ◆ **Oscillator-Generation of femtosecond laser**
  - ◆ **Stretcher-Management of dispersion**
  - ◆ **Amplifier-Boost laser energy**
  - ◆ **Compressor-compensate dispersion for high peak power**
  - ◆ **Enhancement on contrast ratio**
  - ◆ **Typical PW laser facilities in the world**
- ➢ **Ultrafast Laser-Toward Few Cycles and Attosecond Pulse**
- ➢ **Optical Parametric Amplifier-Toward mid-infrared range**
- ➢ **High average power-Toward All-Solid State Amplifier**
- ➢ **Acknowledgement**

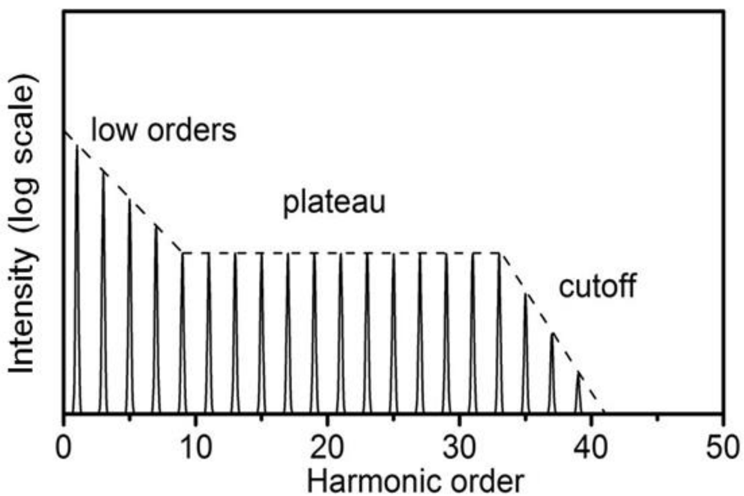
Development of attosecond laser



High-order Harmonic Generation at XUV

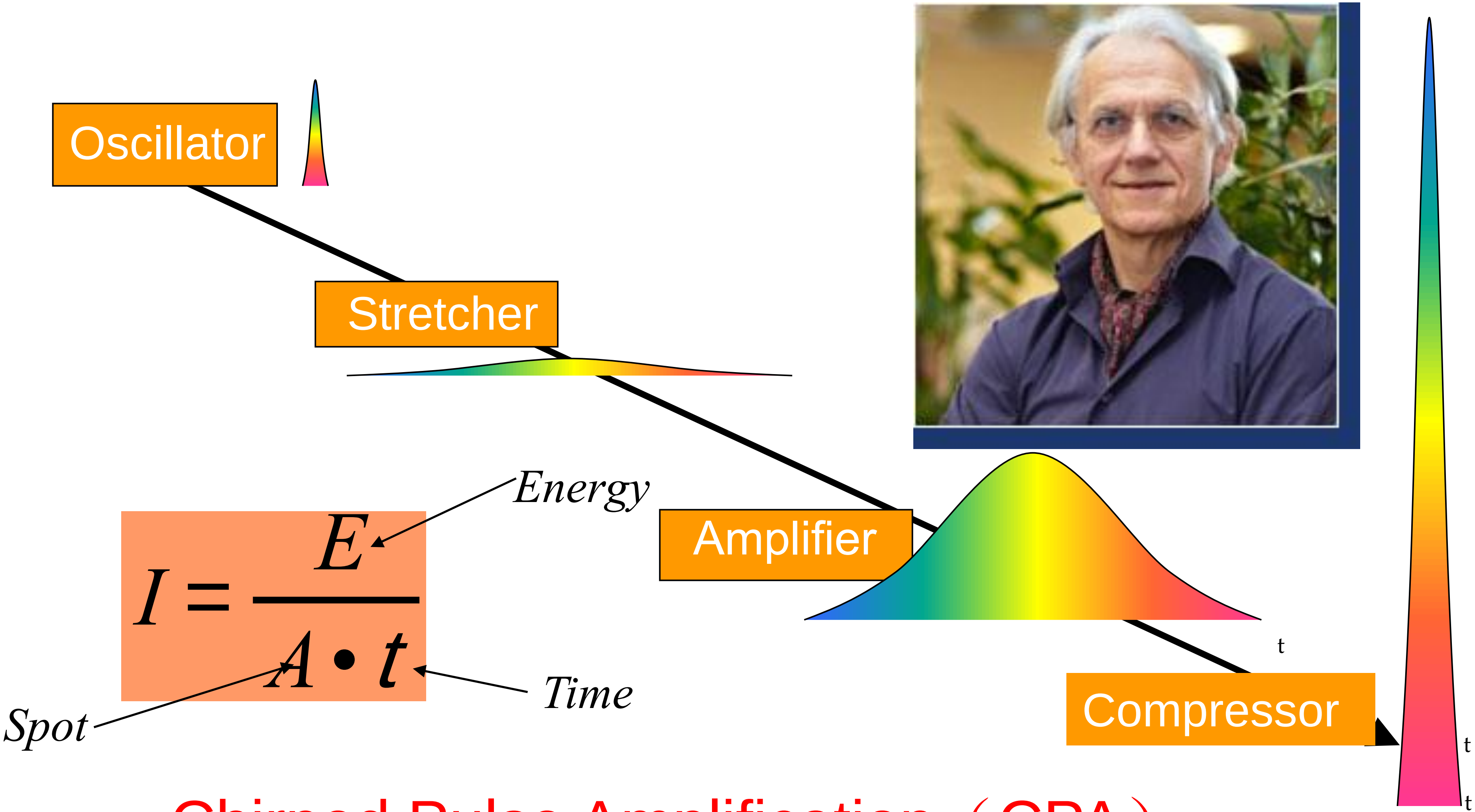






A high intensity femtosecond laser pulse is necessary for HHG and attosecond pulse

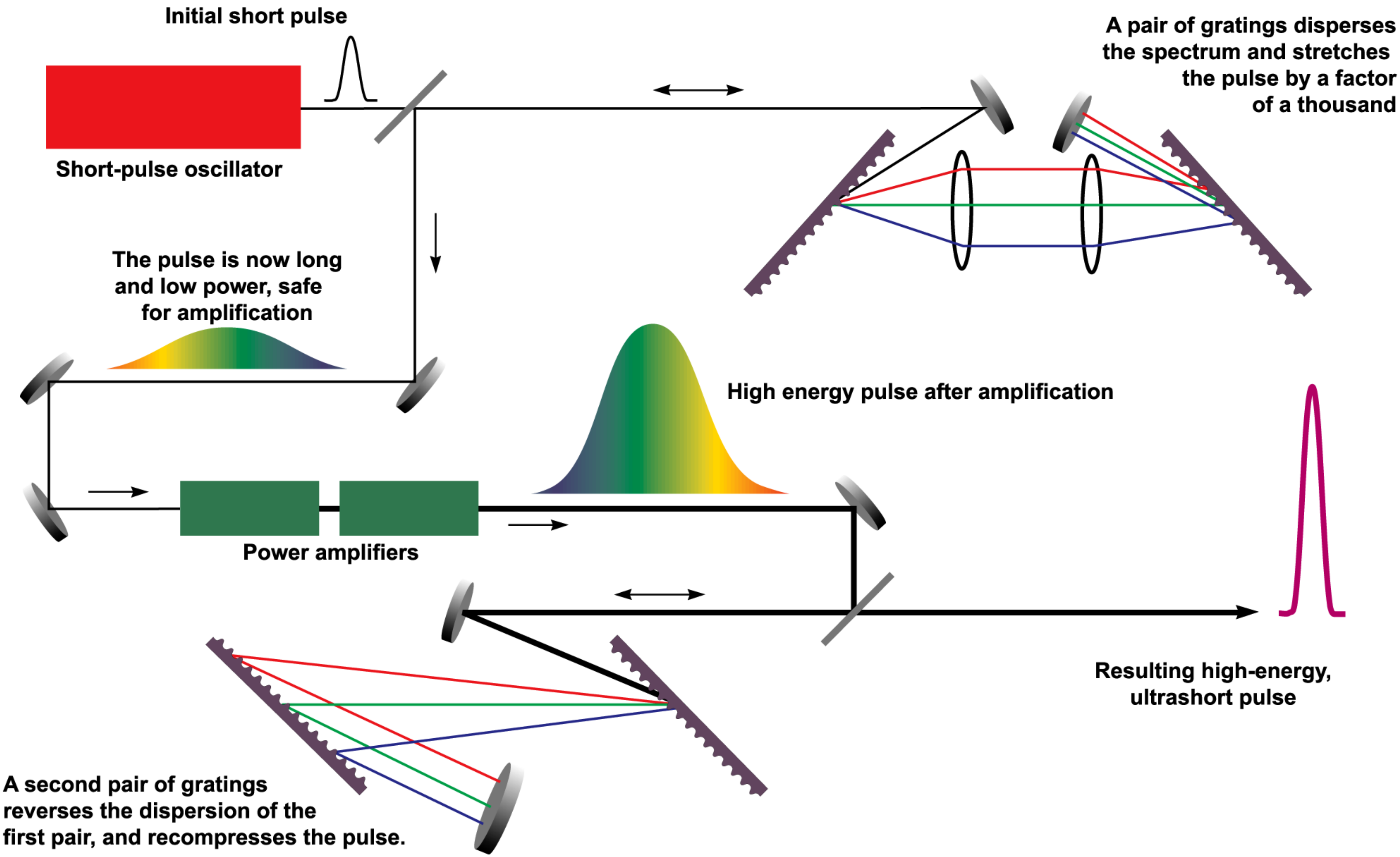
Principle of Chirp Pulse Amplification



Chirped Pulse Amplification（CPA）

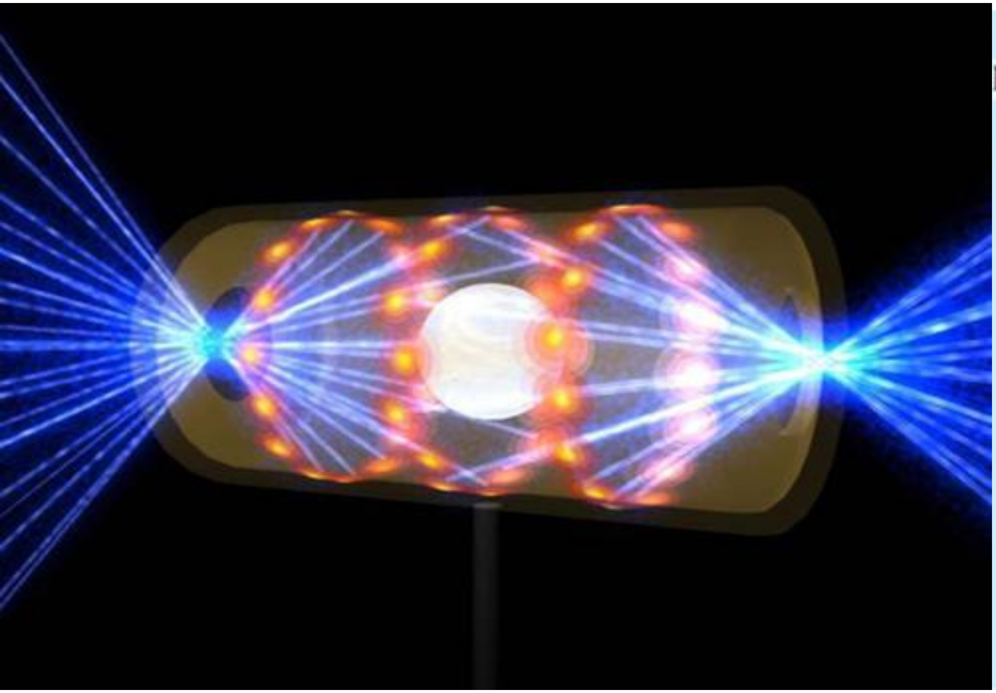
D. Strickland and G. Mourou, *Optics Commun.* **56**, 219 (1985)

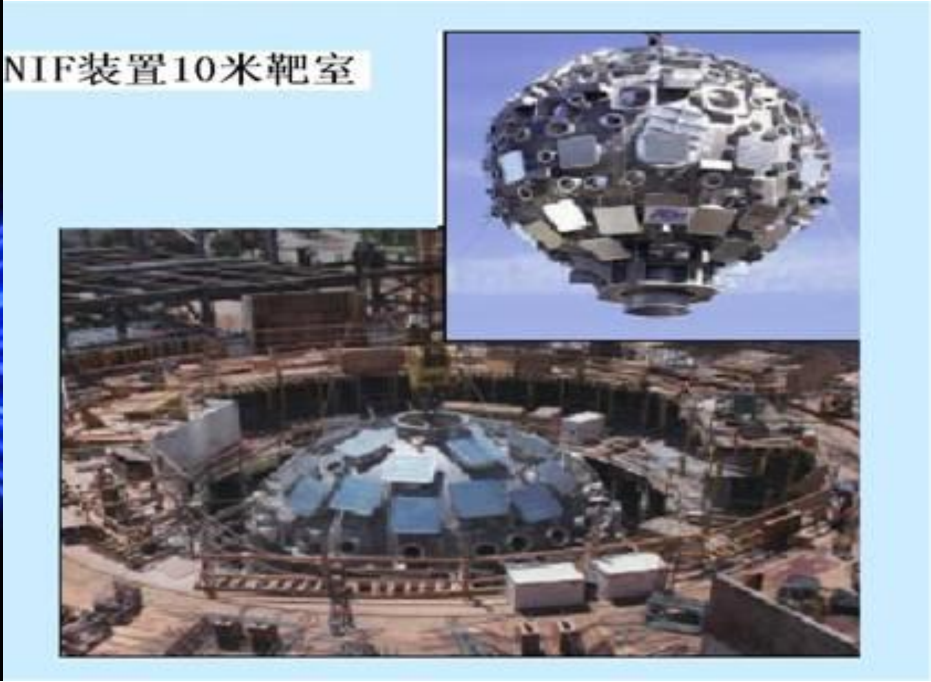
Configuration of CPA



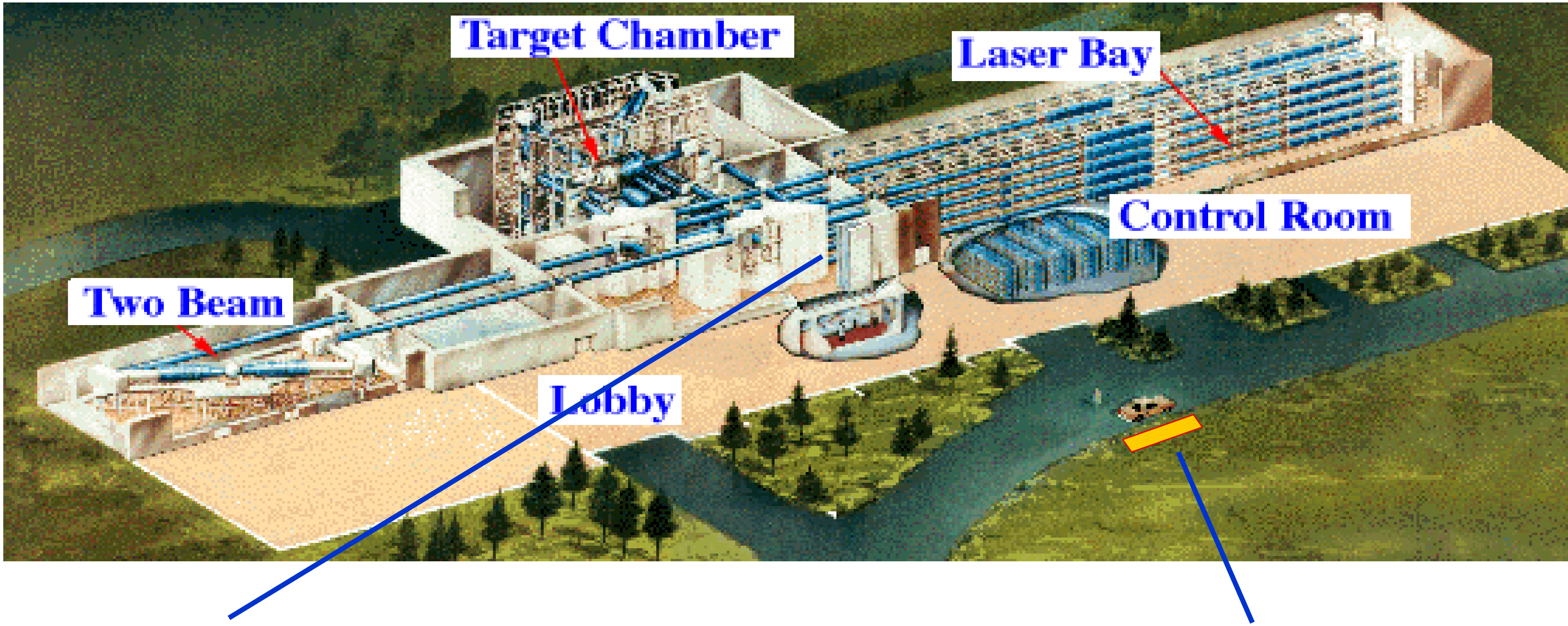
The largest laser facility in the world –National Ignition Facility(NIF)

Energy: 1.8MJ
Pulse: (5-10ns),
Beams: 192,
Peak power: 500TW





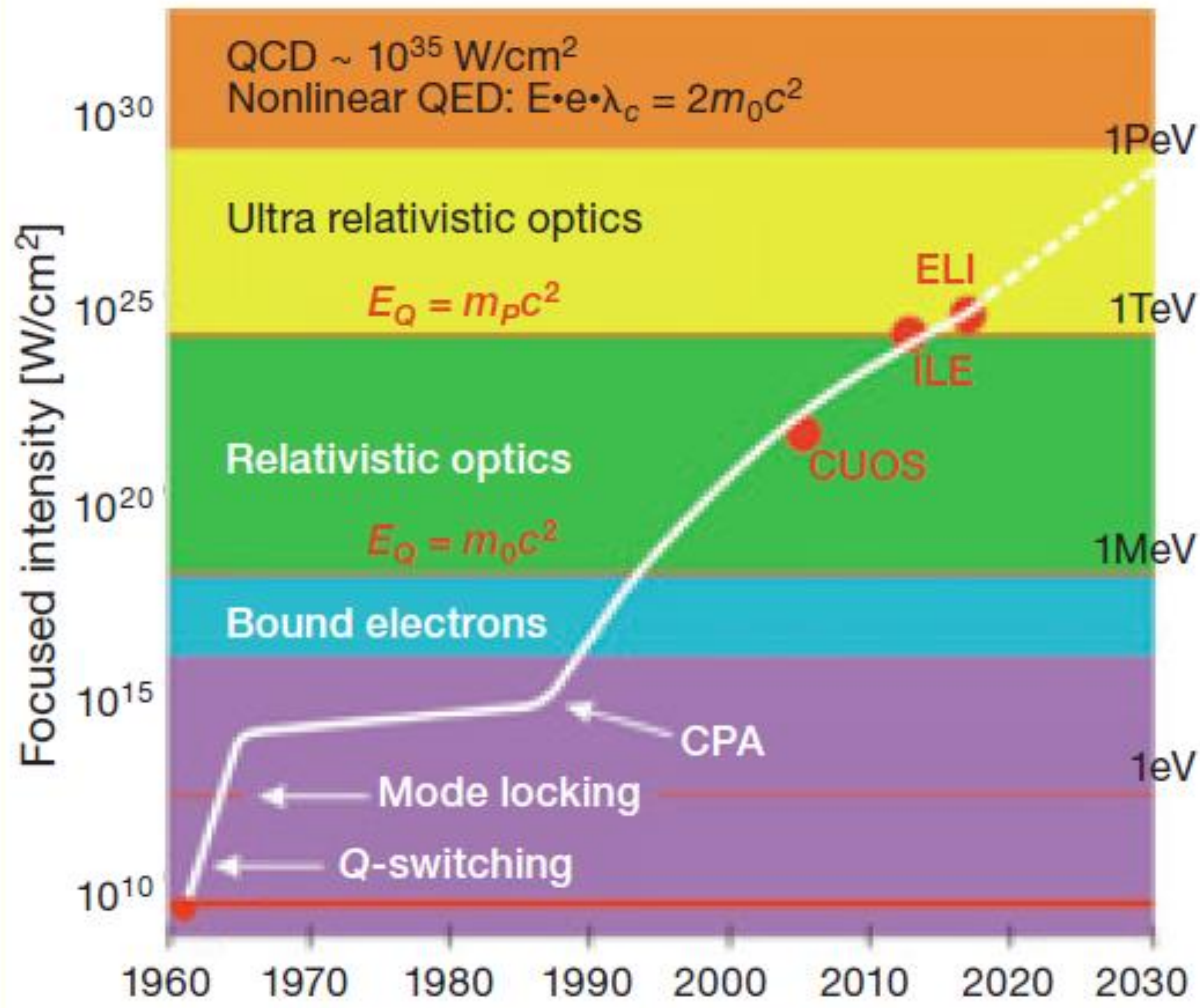
Comparison of Huge Laser Facility and Table-Top Ti:Sapphire CPA laser



Nova
Pulse duration 1 ns
10 kJ/beam
10 beams @ 10 TW/beam = 100 TW
1 shot/hour

Ultrafast Ti:sapphire Amplifier
Pulse duration 15 fs
1.5 J/beam
100 TW/pulse
36,000 shots/hour

Laser Intensity vs. Years



- Nonlinear QED
- Laboratory Astrophysics

- High Energy Physics
- Nuclear physics

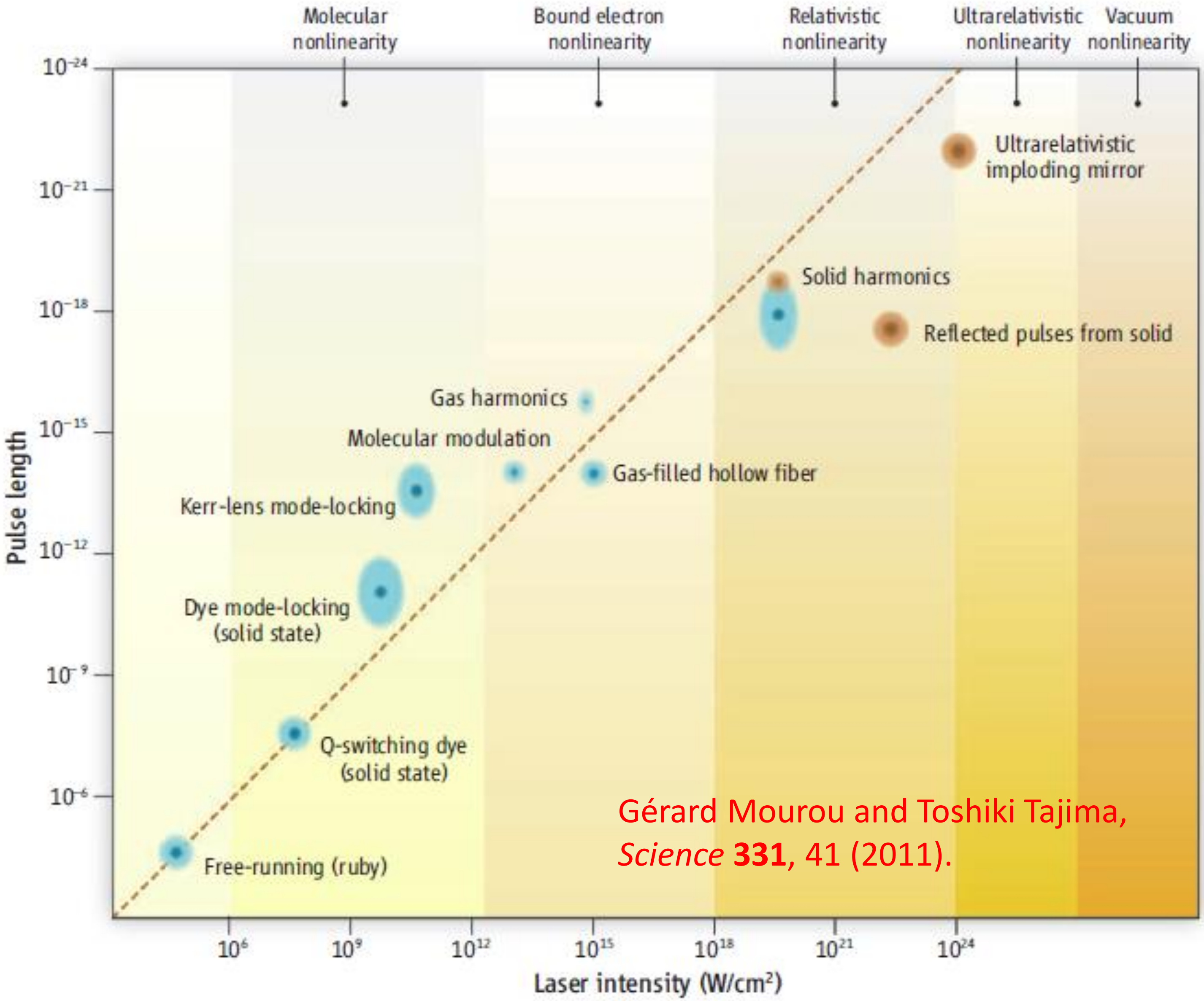
- Ion Acceleration
- Proton Acceleration
- Electron Acceleration

- Isotope Separation
- Coulomb Explosion
- Tunneling Ionization
- High Harmonics Generation
- Above Threshold Ionization
- Multiphoton Ionization

- Nonlinear Optics

Gérard Mourou and Toshiki Tajima, *OPN* **22**, 47 (July/August 2011).

Trend-Toward shorter, more intense



Gérard Mourou and Toshiki Tajima, *Science* **331**, 41 (2011).

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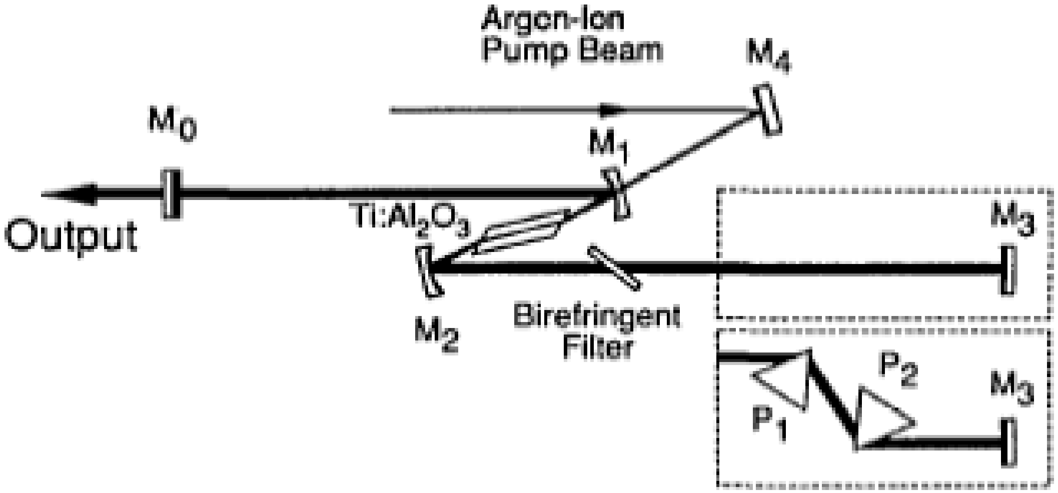
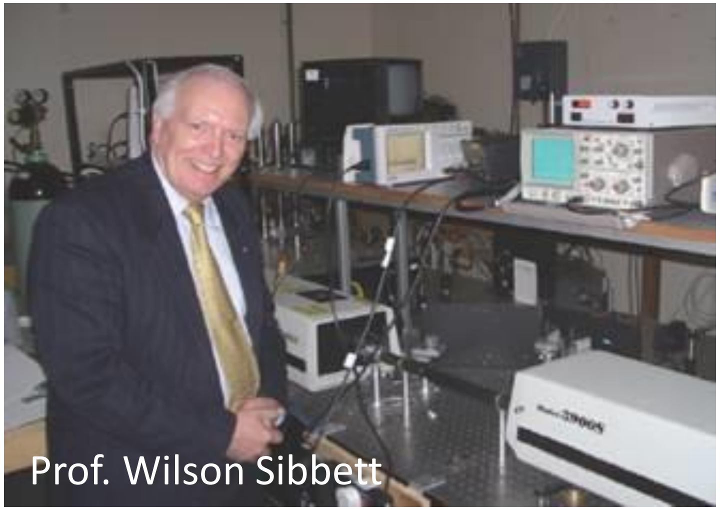
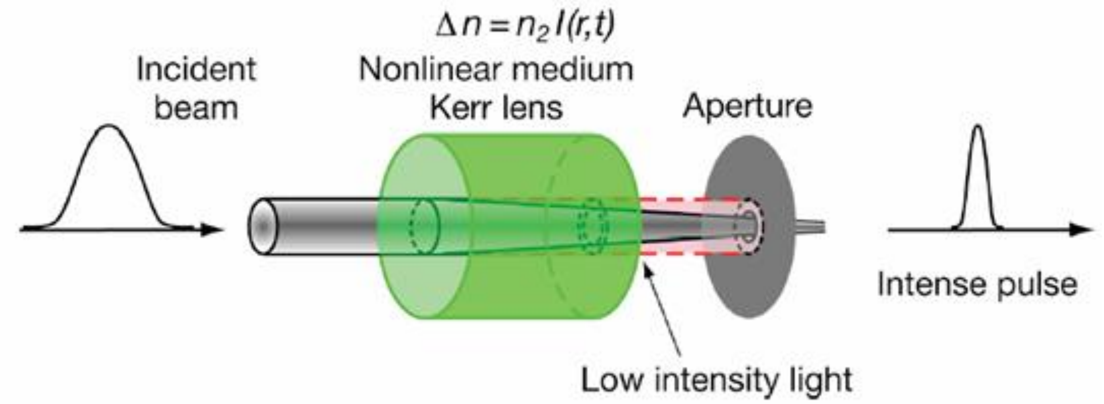
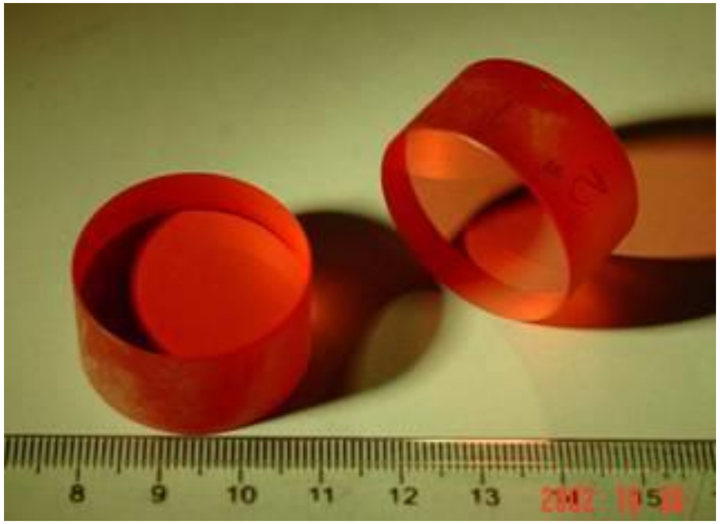
Oscillator-Generation of femtosecond laser

The discovery of KLM Ti:Sapphire laser



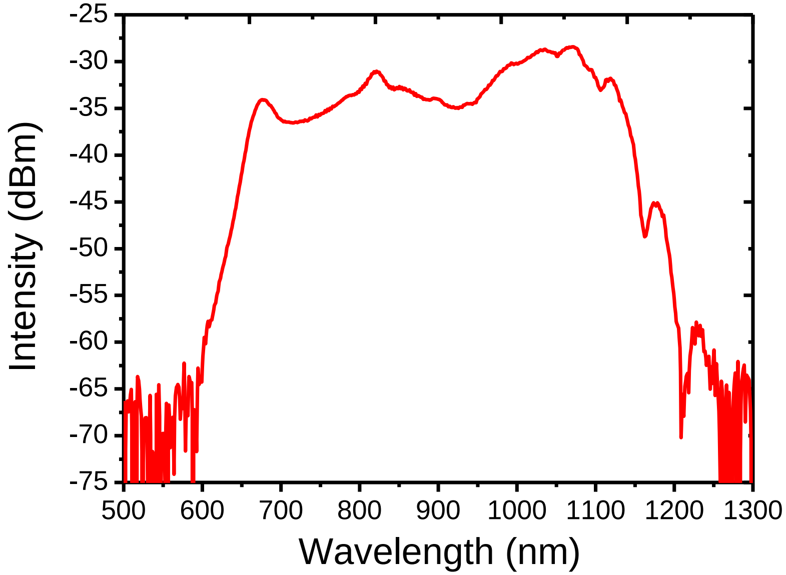


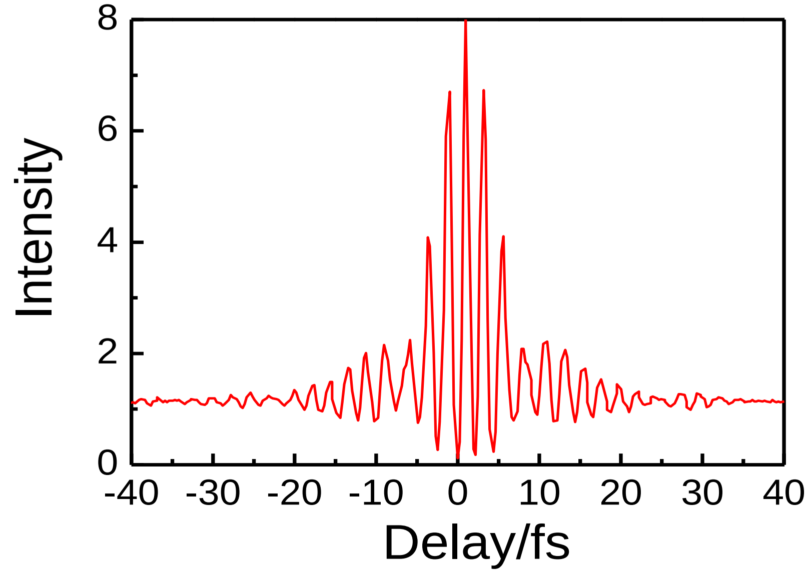


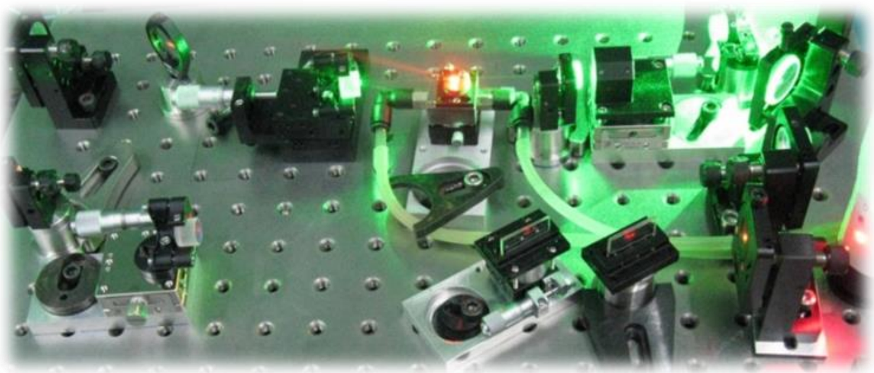


D. E. Spence et al, Opt. Lett. 16, 42, 1991

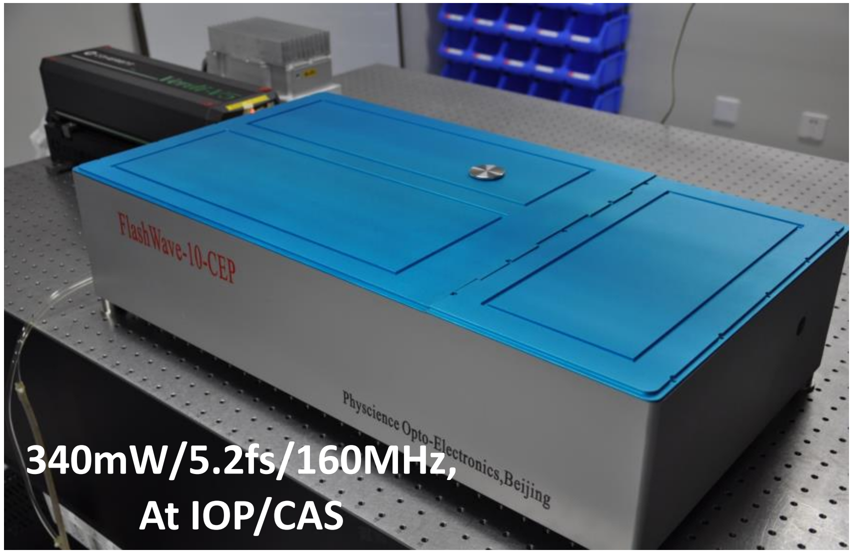
A typical sub-10fs KLM Ti:Sapphire laser



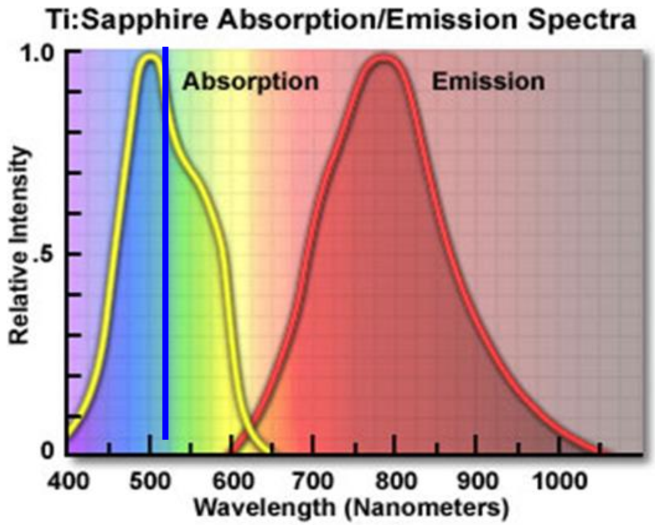




Ti:S laser is capable of the shortest pulse duration and the most broad spectrum, but lower power and high cost.



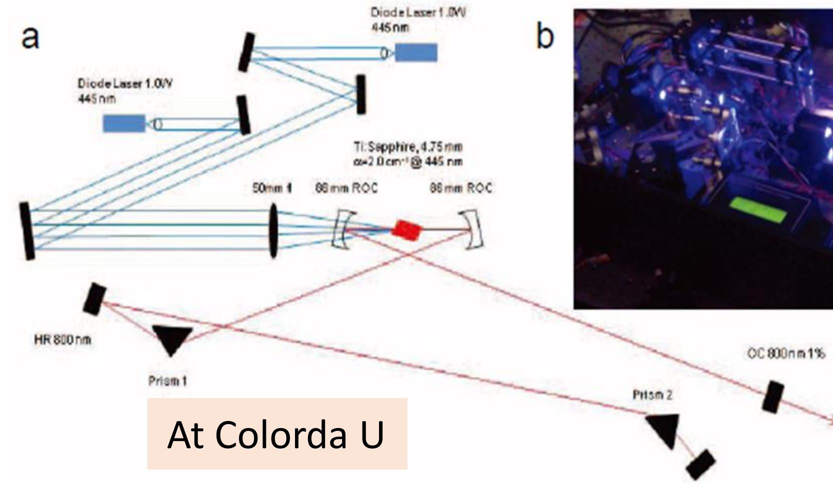
fs Ti:Sapphire lasers pumped with blue lasers

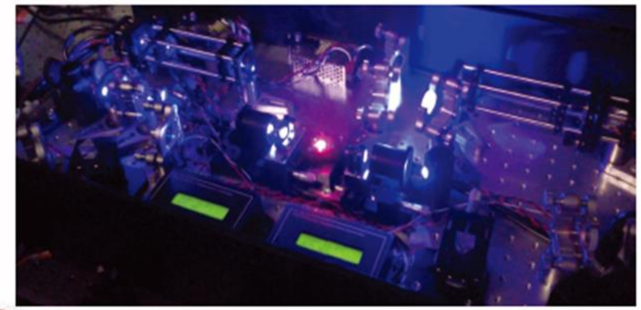


Peak absorption wavelength of Ti:sapphire crystal at 490nm.

Comparison of two pump lasers

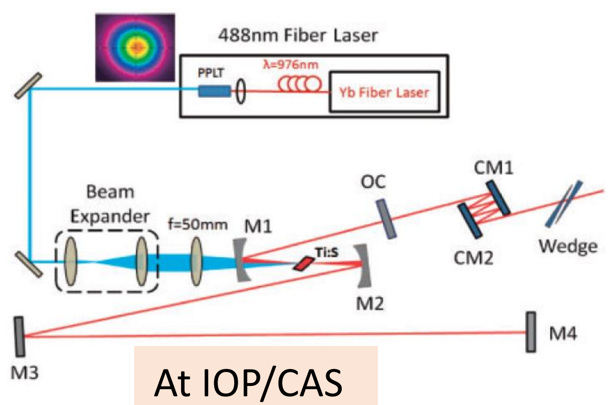
Pump laser	Laser Diode	Fiber Laser
Pump Wavelength	445nm	488nm
Pump power	2.4W	1.5W
Absorption	60%	92%
Pulse duration	15fs	8.7fs
ML power	34mW	150mW(3%) 60mW(0.5%)

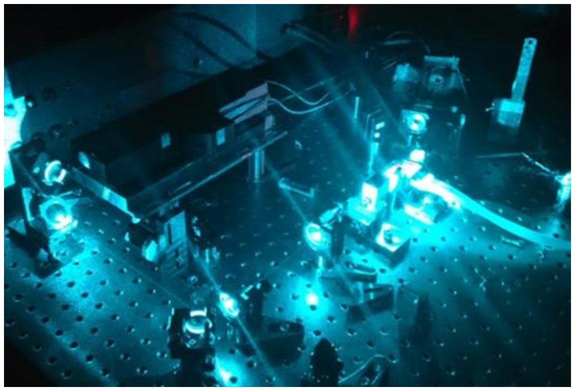




Opt Express
Vol. 20,13677(2012)
At Colorda U.

450nm blue laser diode pumped fs Ti:sapphire laser





488nm blue fiber laser pumped fs Ti:Sapphire laser

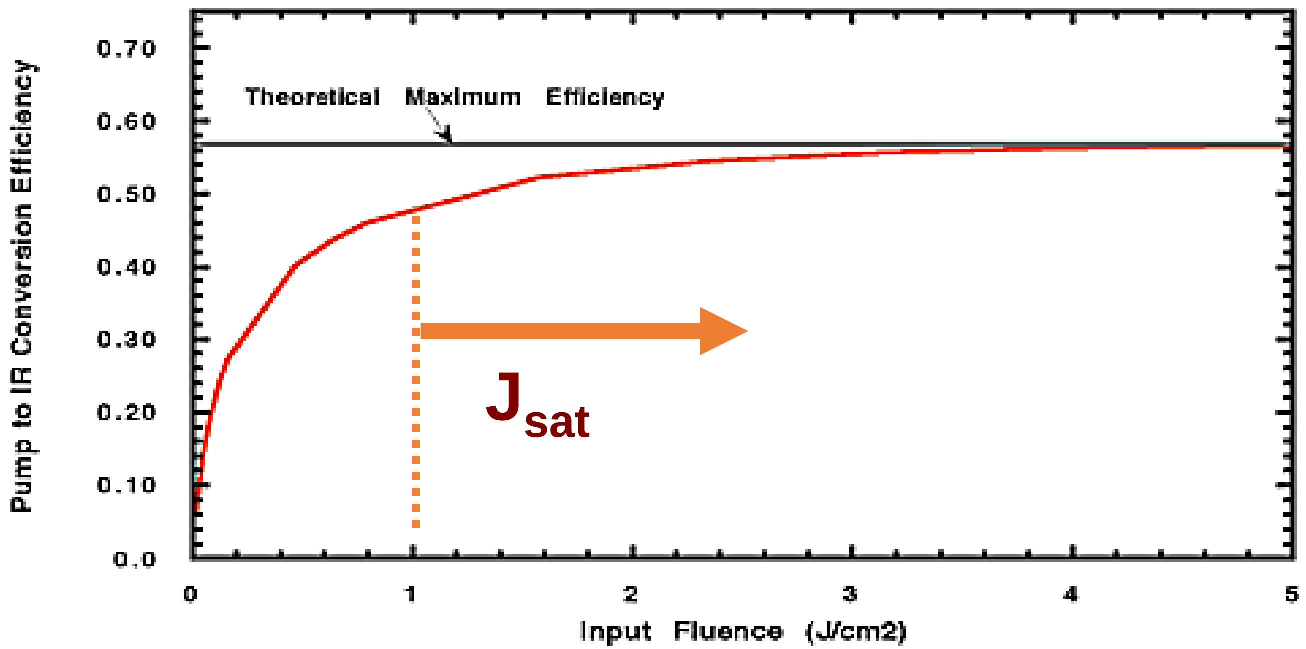
Z. J. Yu *et al*, Low-threshold sub-10fs mode-locked Ti:Sapphire laser pumped by 488nm fiber laser, Appl Phys Express, 7, 102702(2014)

Stretcher-Management of dispersion

Saturation fluency in laser medium

- **High Efficiency in Final Amplifier**

  Run above the saturation fluency



- **Produce the shortest duration pulses**

  Run near the fluorescence limit

- **No Damage**

  Run below the dielectric breakdown limit < 5×10^9 W/cm^2

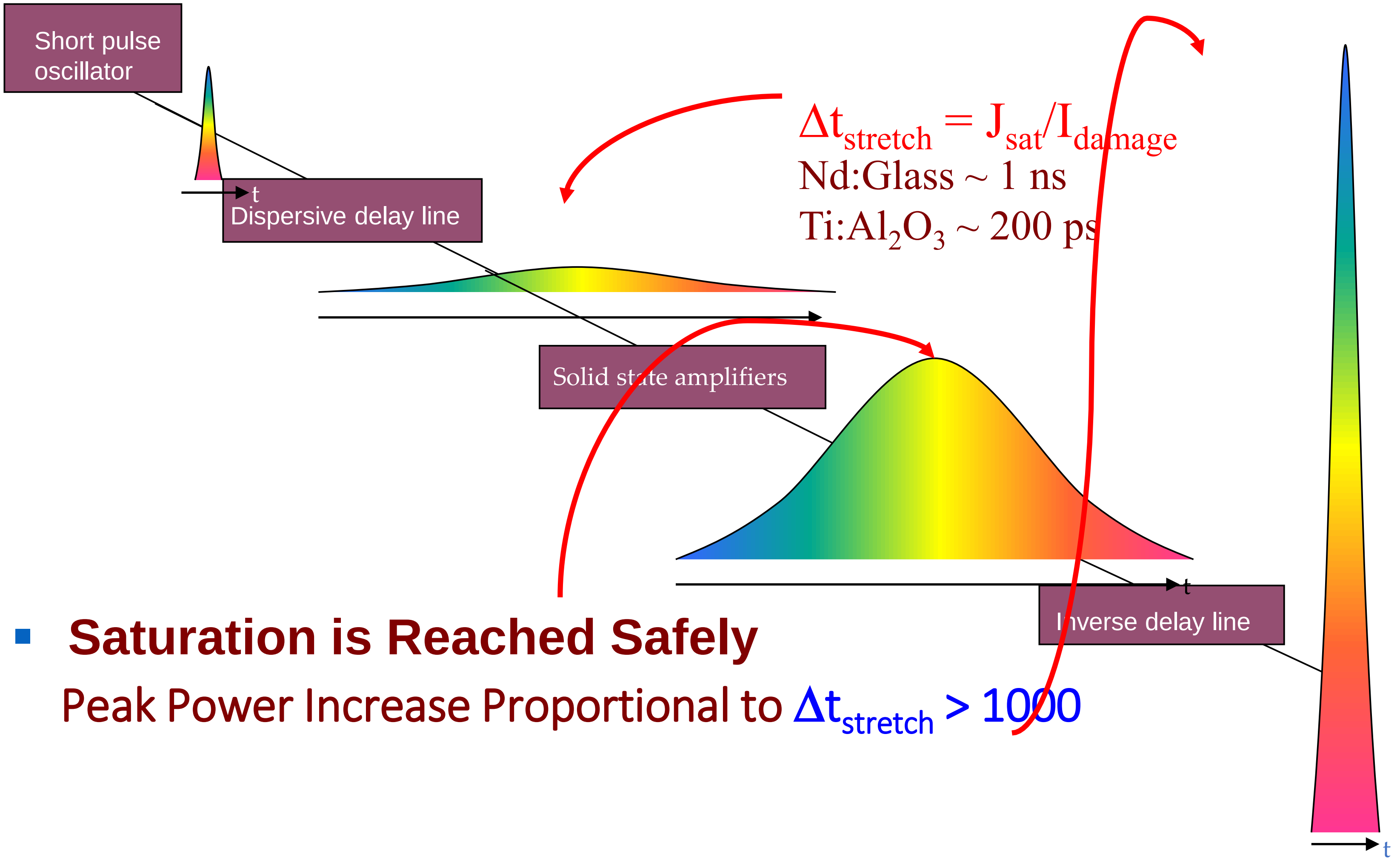
Maximum Intensity at Saturation for some laser media

Material	Jsat (J/cm²)	Δtmin (fs)	Imax (W/cm²)
Nd:Silicate	6	60	10^{14}
Yb:Silicate	32	20	1.6×10^{15}
Ti:Sapphire	1	3	3.3×10^{14}

- **Maximum output intensity = $J_{sat} / \Delta t_{min}$**
- **However, damage threshold < 5×10^9 W/cm²**

Conclusion:
We must reduce pulse INTENSITY during amplification

Safe saturation in amplification



- **Saturation is Reached Safely**

  Peak Power Increase Proportional to $\Delta t_{stretch} > 1000$

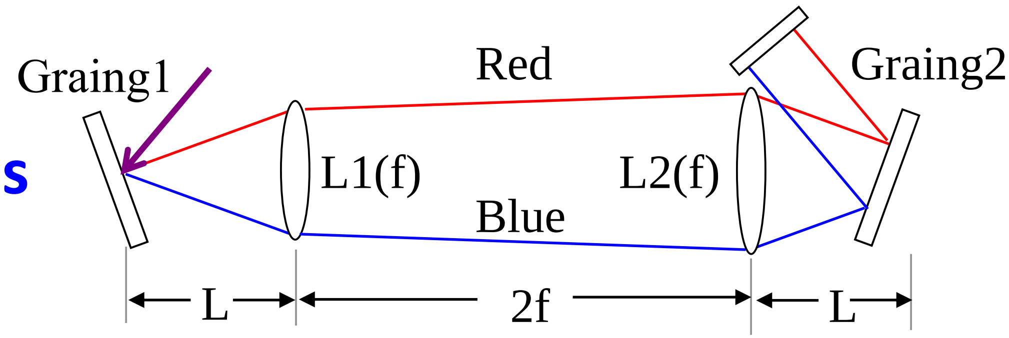
Conclusion:

Stretch laser pulse duration in necessary before amplification

A type of typical stretchers

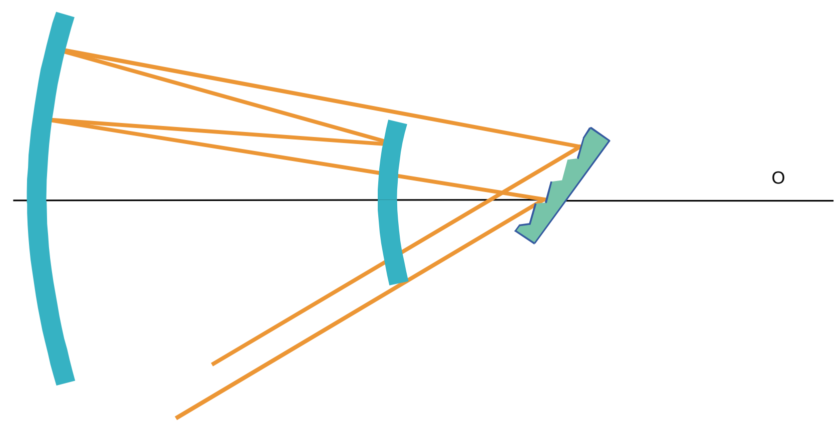
- **Martinez Stretcher**

  aberration, can not compress pulse shorter than 50fs



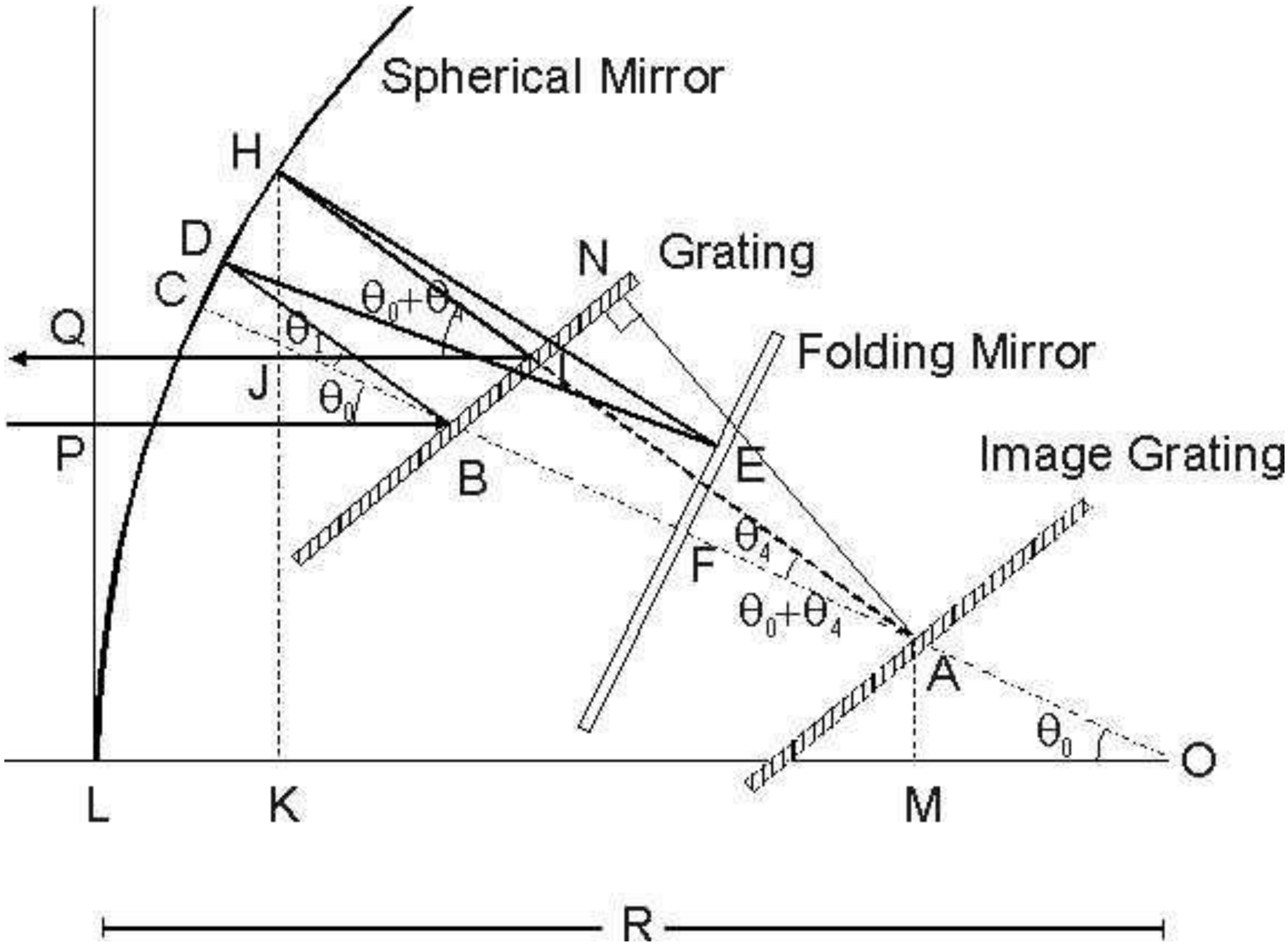
- **Öffner Stretcher**

  free aberration, most widely use today



- **Material Stretcher**

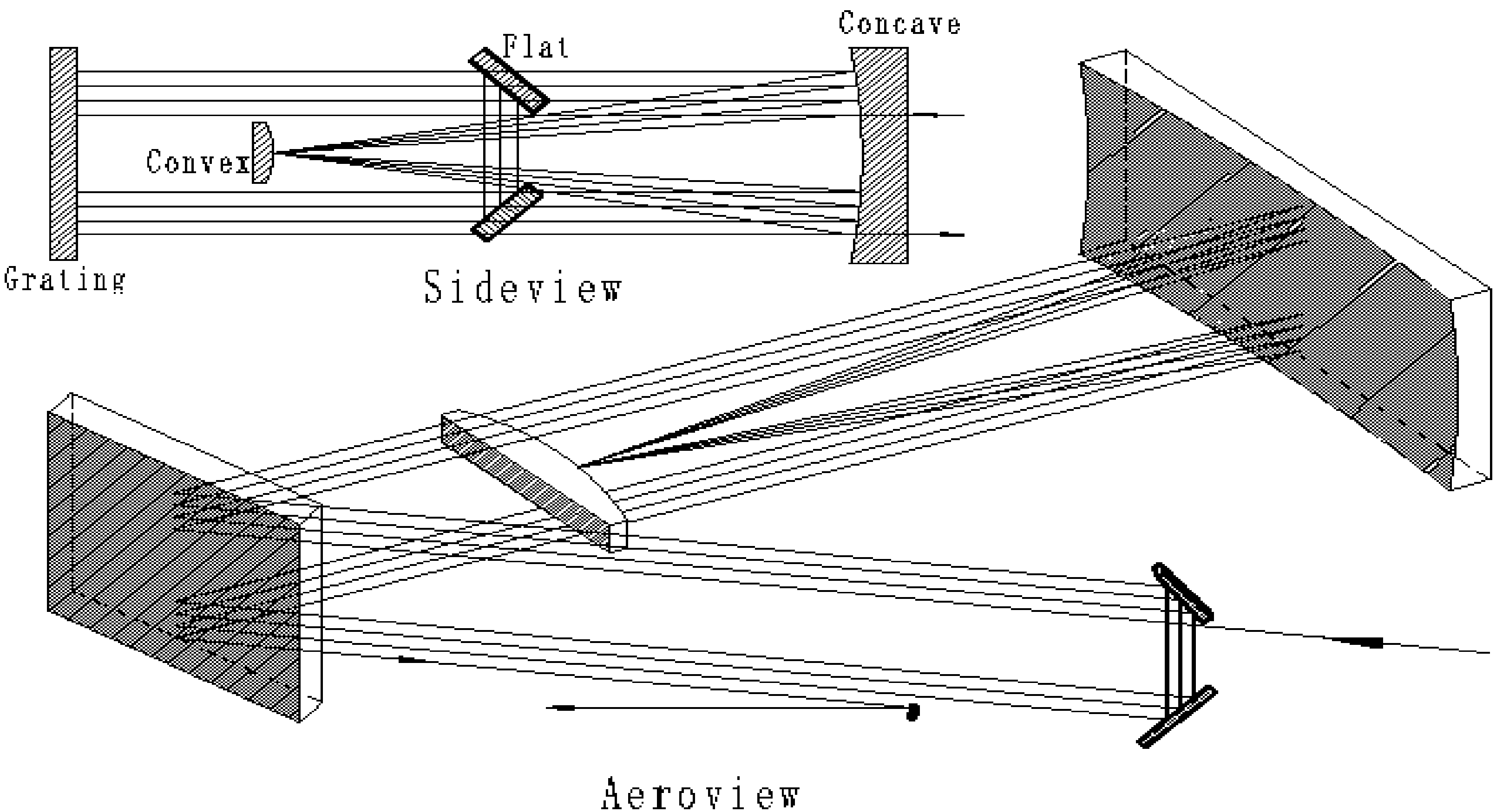
  Use high dispersion material, suit for 10fs⟹ ~10ps



$$\varphi(\omega) = \frac{\omega}{c}(C + A) - \frac{\omega}{c} b \times [1 + \cos(\theta_0 + \theta_4)] + \frac{2\pi G}{d} \tan(\gamma - \theta_0 - \theta_4) + \frac{2\pi}{d}(G_0 - G) \tan(\gamma - \theta_0)$$

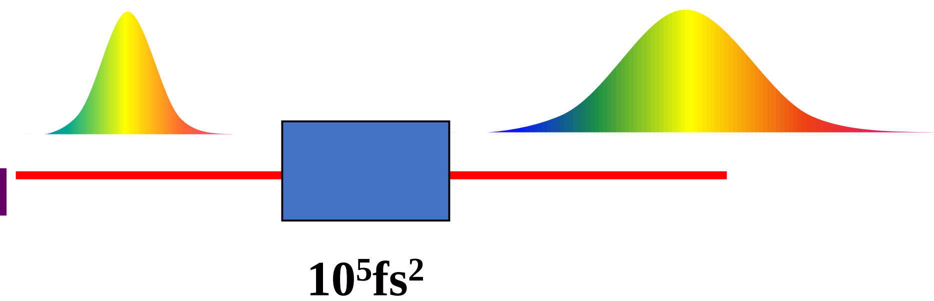
J. Jiang, Z. Zhang, T. Hasama, J. Opt. Soc. Am. B, 19(4): 678~683(2002)

Doubled Stretcher



Dispersion in Optical Materials

Laser will suffer dispersion when propagate in optical materials. The phase depend on the optical path with wavelength:



$$\phi_m(\omega) = Ln(\omega)\omega / c$$

$$GD = \frac{d\phi_m(\omega)}{d\omega} = \frac{L_m}{c}\left(n(\lambda) - \lambda \frac{dn(\lambda)}{d\lambda}\right)$$

$$GVD = \frac{d^2\phi_m(\omega)}{d\omega^2} = \frac{\lambda^3 L_m}{2\pi c^2}\frac{d^2 n(\lambda)}{d\lambda^2}$$

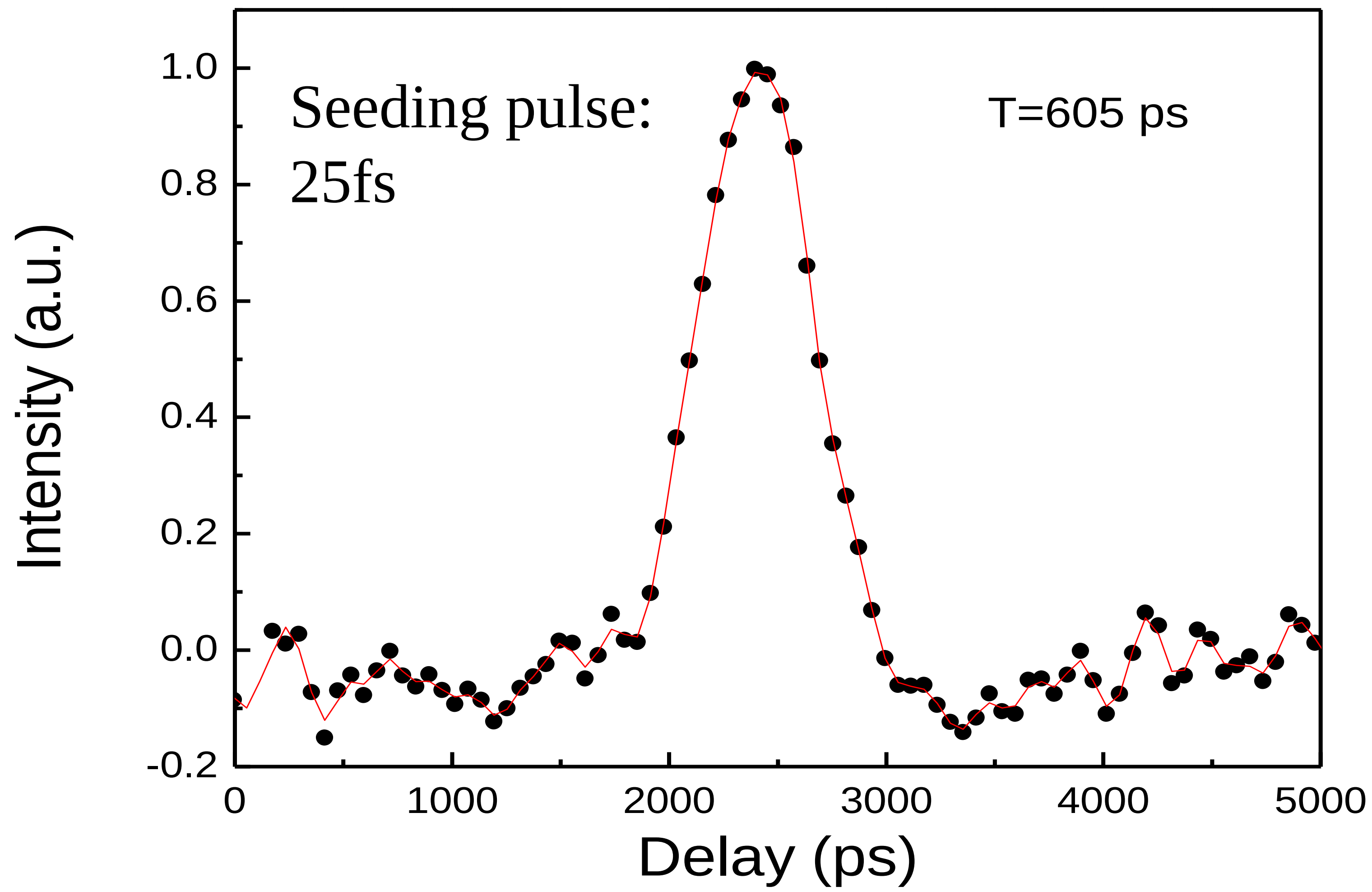
$$TOD = \frac{d^3\phi_m(\omega)}{d\omega^3} = -\frac{\lambda^4 L_m}{4\pi^2 c^3}\left(3\frac{d^2 n(\lambda)}{d\lambda^2} + \lambda \frac{d^3 n(\lambda)}{d\lambda^3}\right)$$

$$\frac{\tau}{\tau_0} = \sqrt{1 + \left(\frac{4 \cdot \ln 2 \cdot GVD}{\tau_0^{\,2}}\right)^2}$$

5fs → $10^5 fs^2$ → 55ps

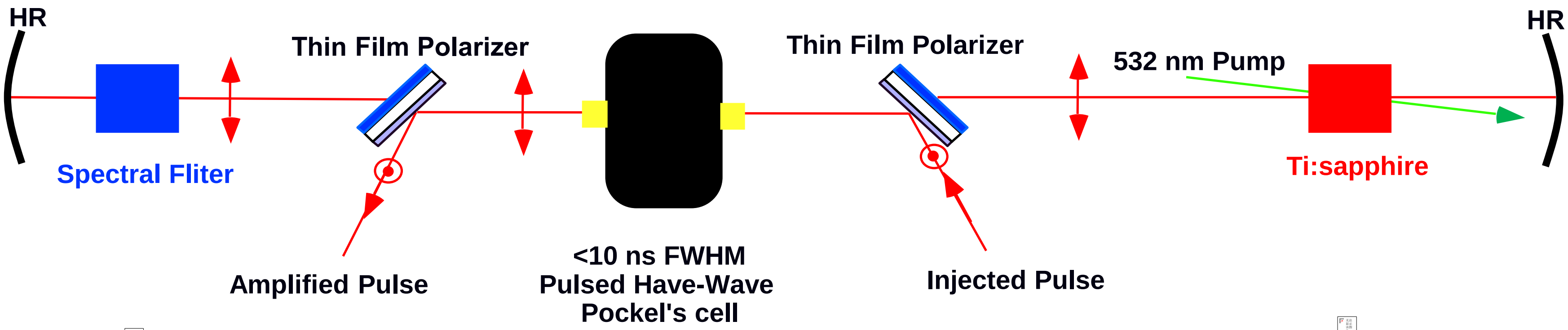
30fs → $10^5 fs^2$ → 9ps

Pulse duration after Öffner stretcher



Amplifier-Boost laser energy

1. Regenerative amplifier and Pulse Shaping



$T(\omega)$

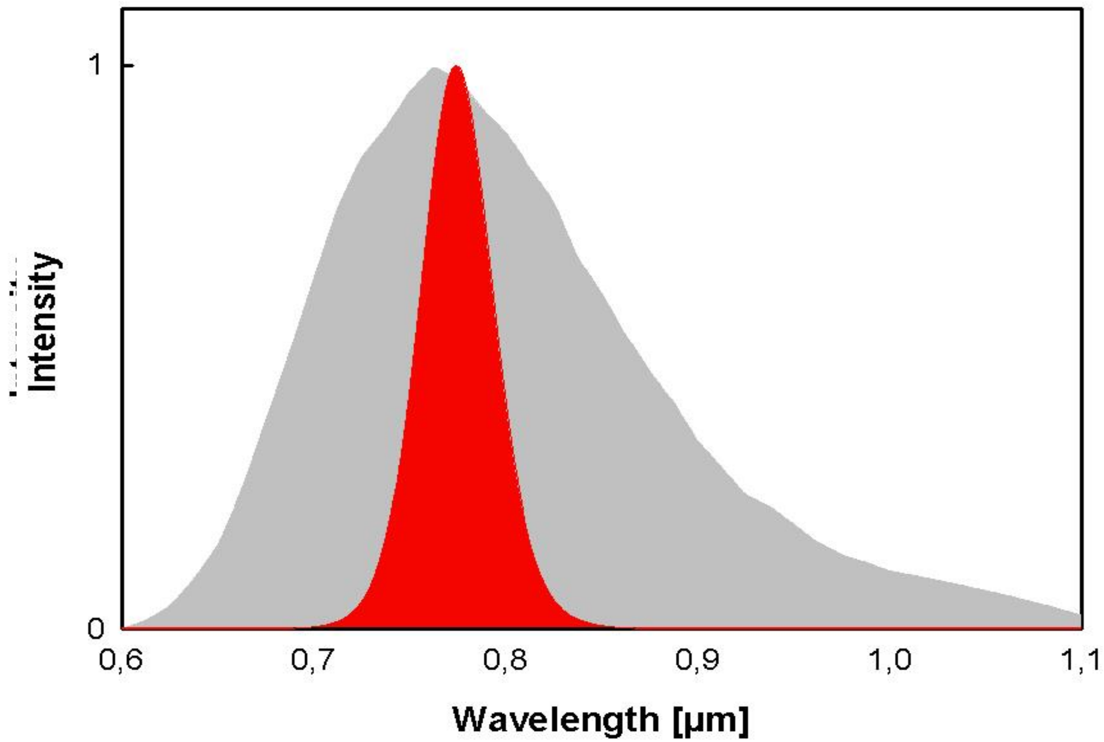
$G(\omega) = e^{g(\omega)L}$

$$Net\ Gain = [T(\omega)G(\omega)]^{n=\#of\ passes}$$

- Most gain narrowing occurs in the regen or preamp
- Correct for gain narrowing on each round trip
- Relatively low gain per pass means we only need a linear filter

Gain narrowing effect

$$G(\omega) = \exp\left[\frac{\omega L}{c}\chi''(\omega)\right]$$



Approaches to Control Gain Narrowing

- Regenerative pulse shaping

    Correct for the gain narrowing on each pass trip

- Minimize systems losses

    Multi-pass amplifiers with high gain per pass

- Seed to the RED of the line center

    Regen or multi-pass

    Play off saturation pulling against gain shifting

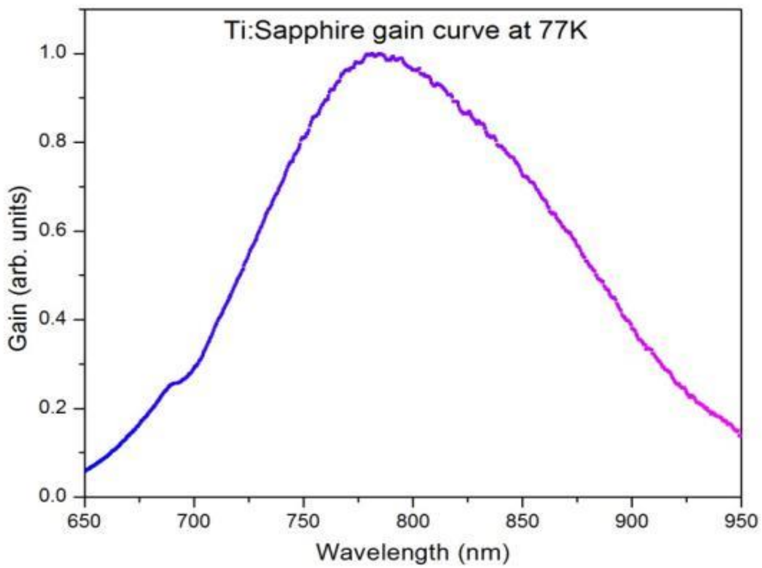
- Mix amplifier materials

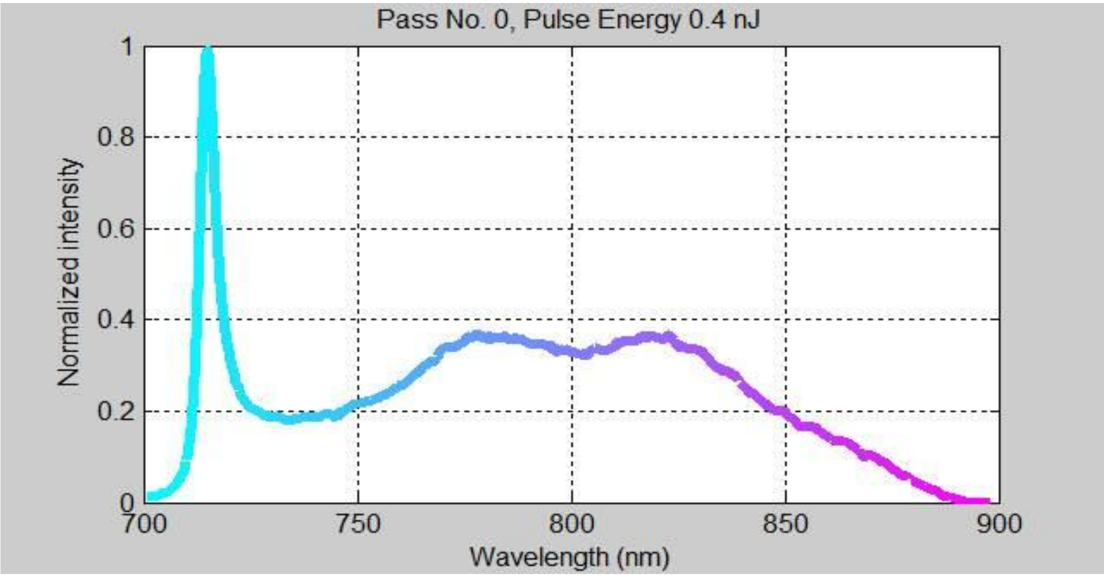
    Different center frequency yields higher overall gain bandwidth

- OPCPA (Optical Parametric CPA)

    Large gain bandwidth in parametric amplification

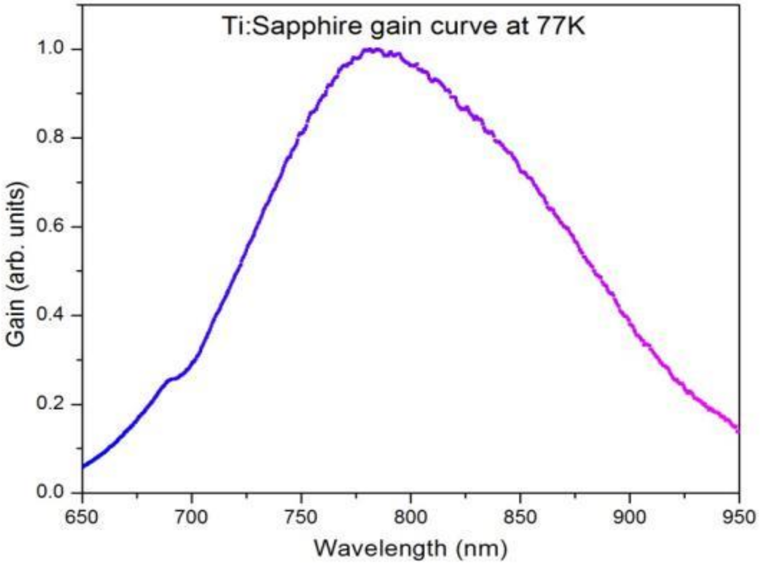
Gain Narrowing

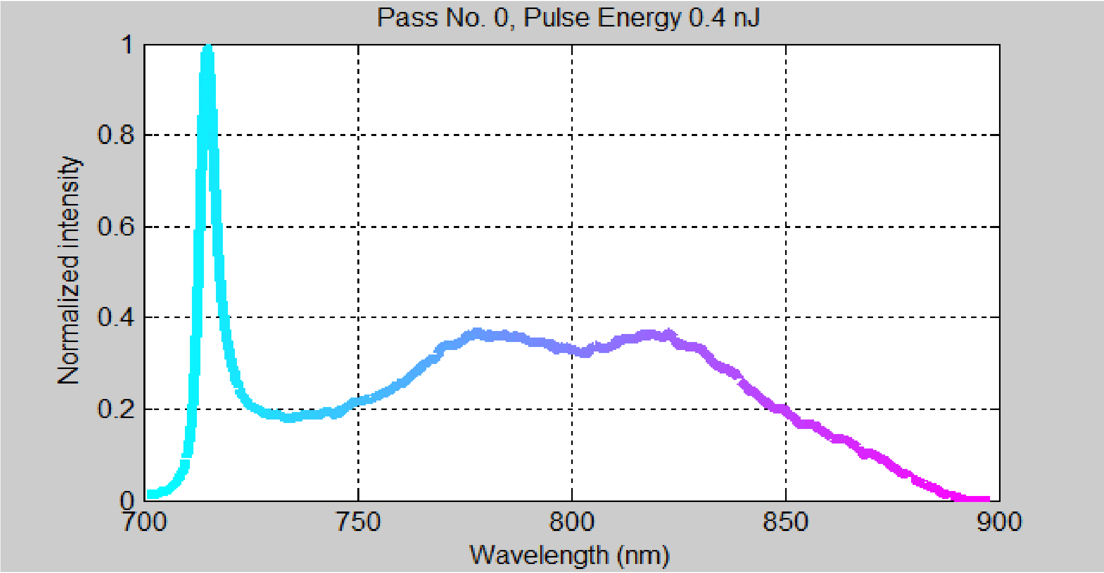




nJ → J, amplification of 10^9 times

Gain Narrowing

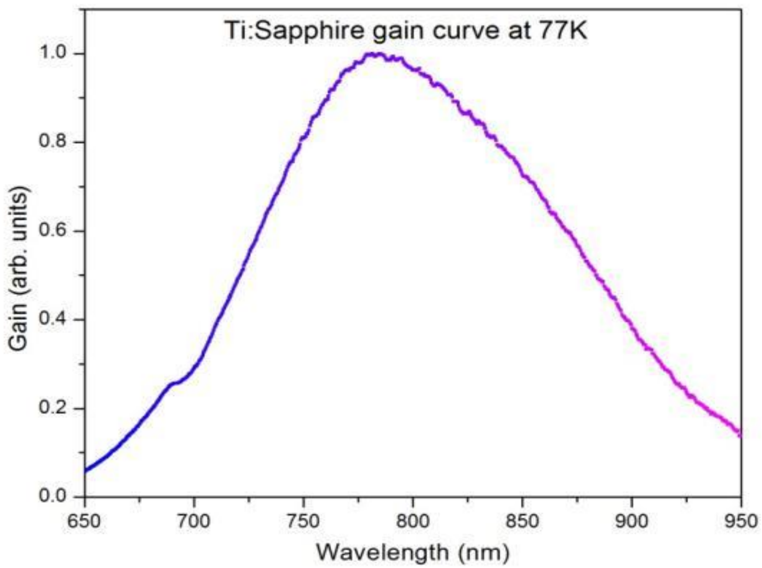


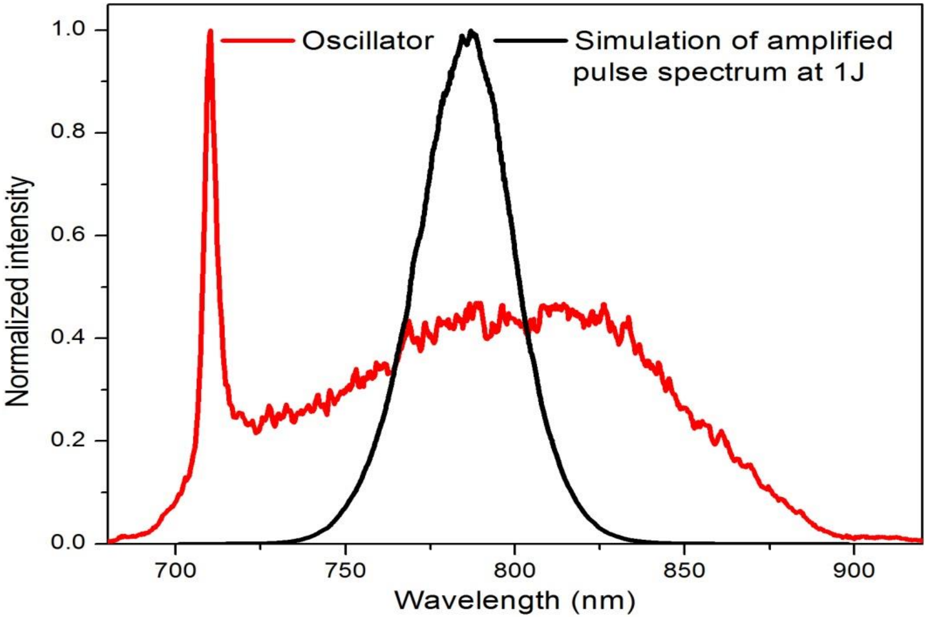


nJ → J, amplification of 10^9 times

Gain Narrowing

Final output pulse duration ~30-40 fs

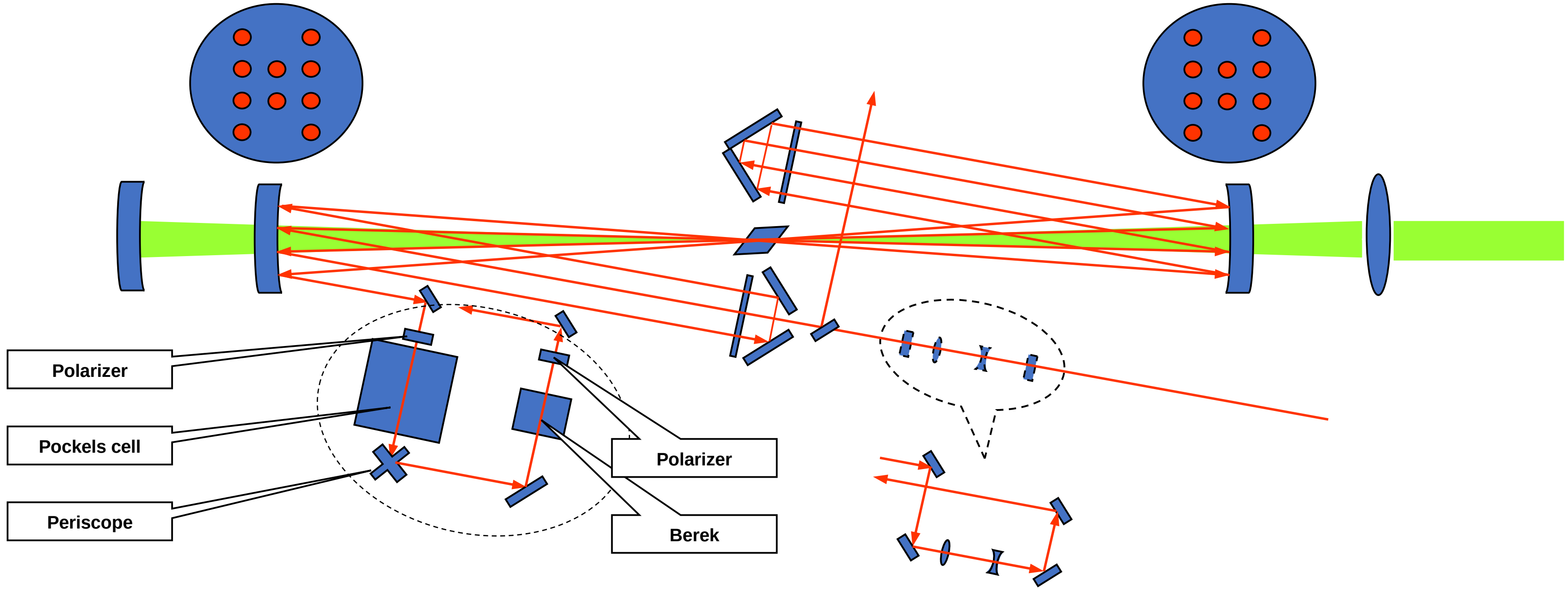




nJ → J, amplification of 10^9 times

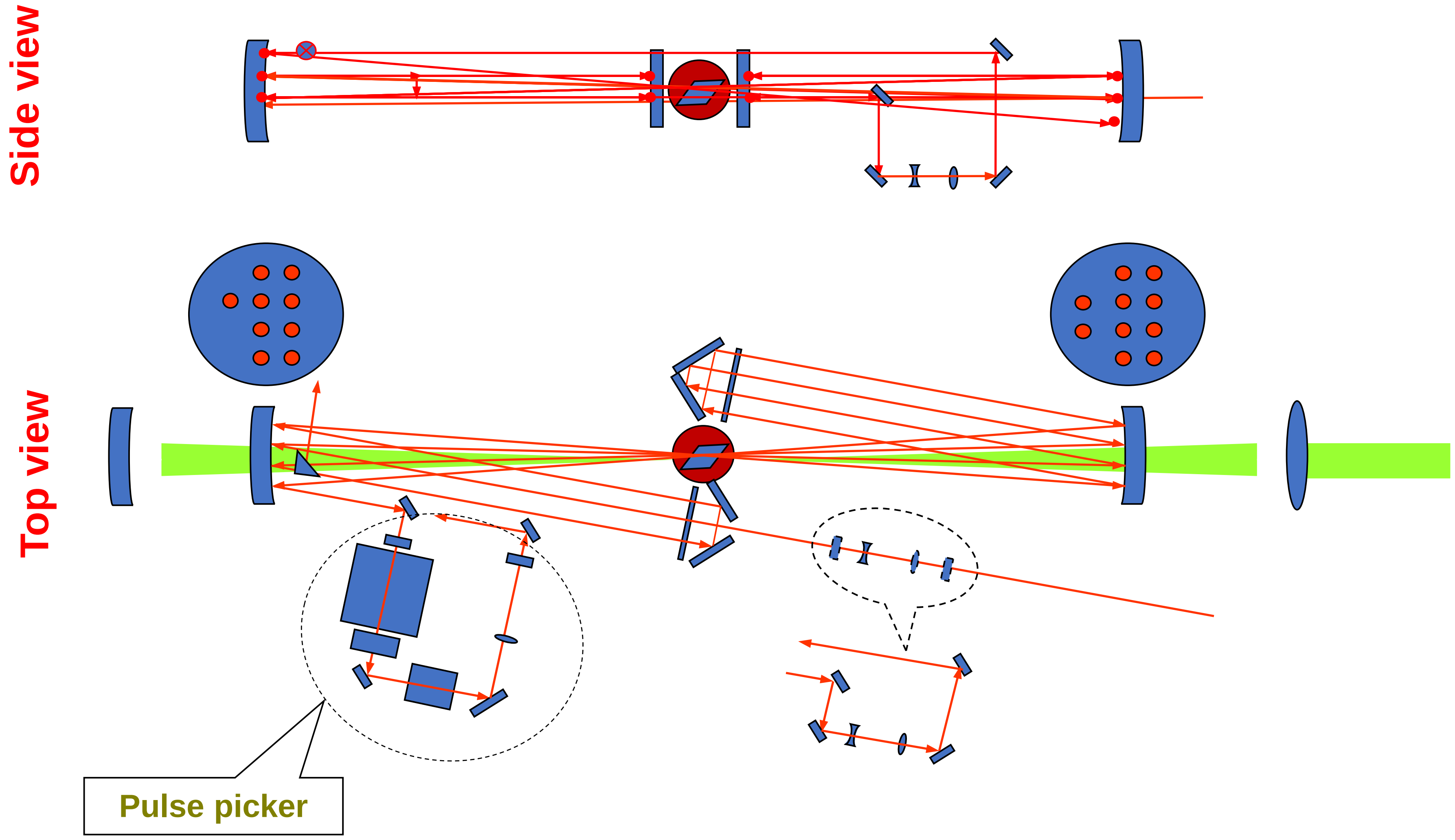
2. Multi-pass amplifier

10 pass preamplifier

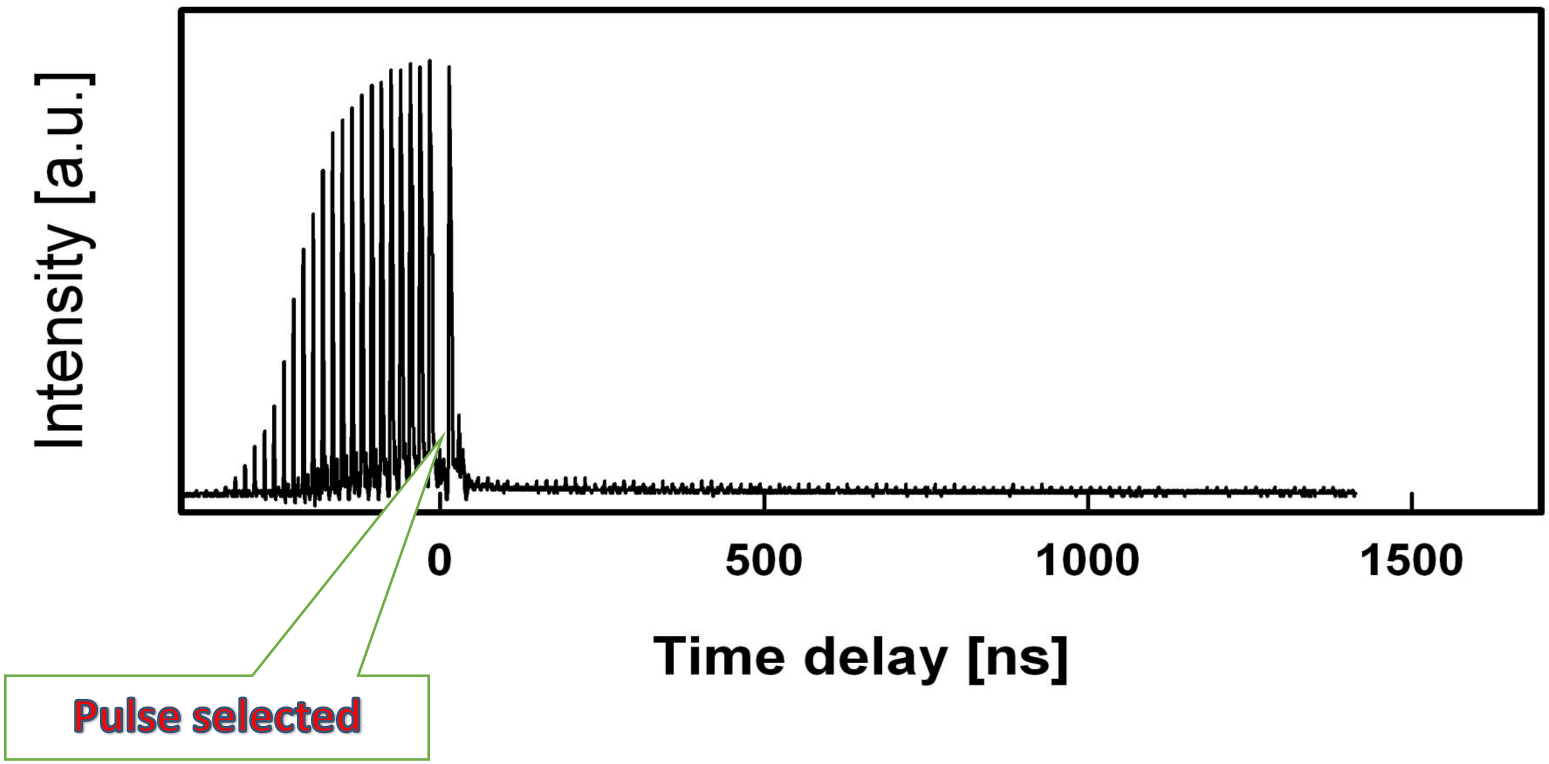


Z.Cheng, F.Krausz, Ch.Spielmann, Opt. Commun 201, 145 (2002)

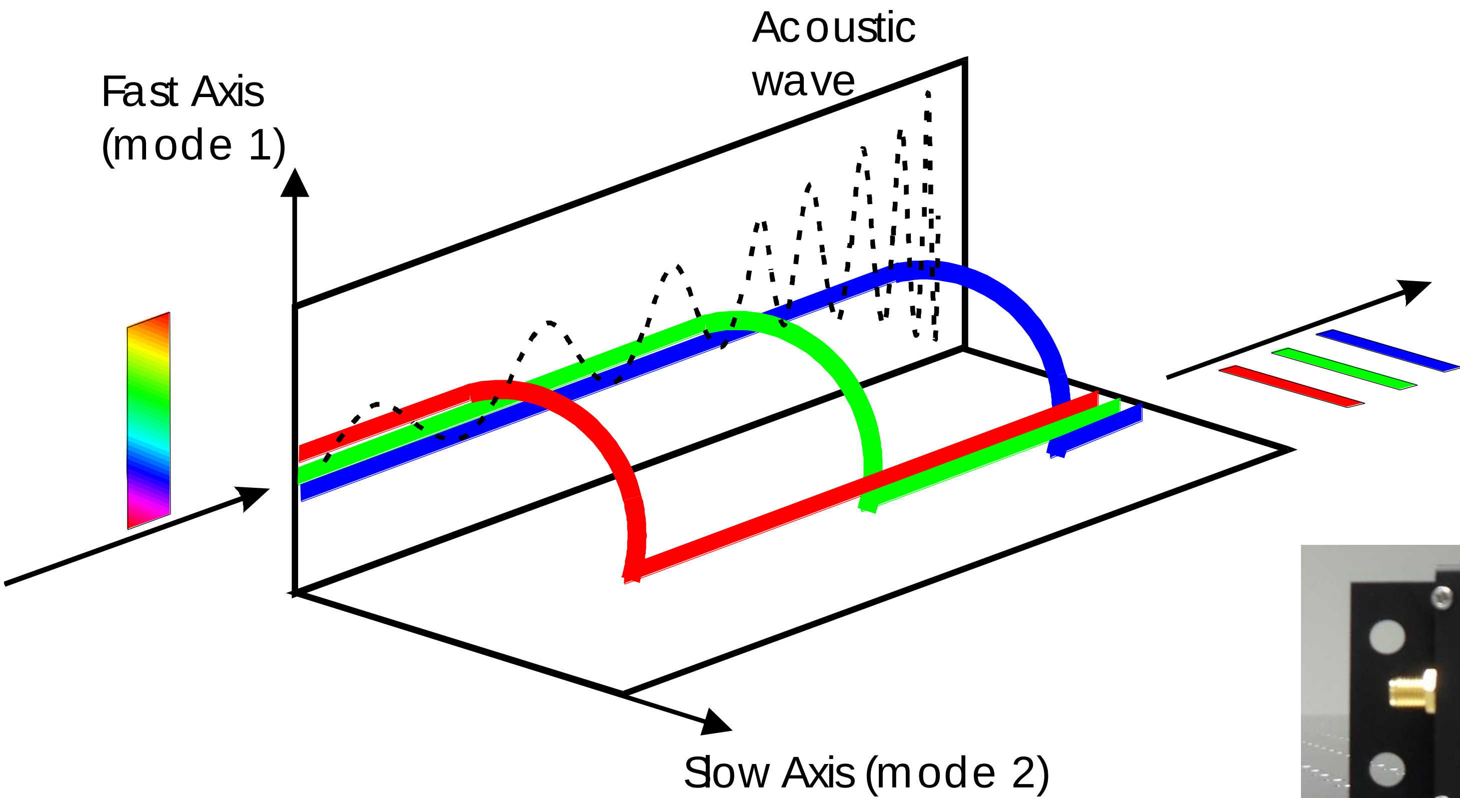
10-pass Chirped pulse amplifier



Evolution of amplification gain saturation



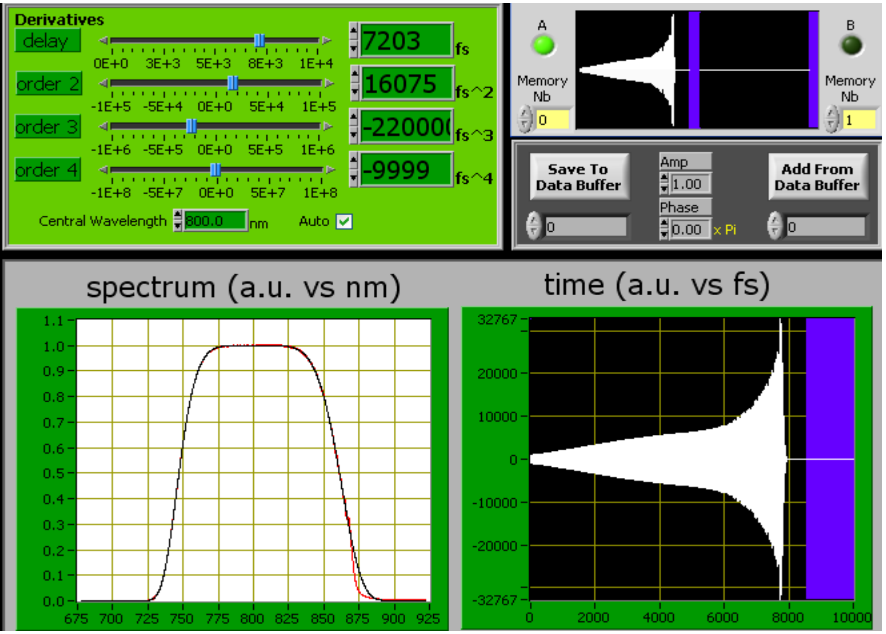
3. Spectrum Shaping Control with AOPDF

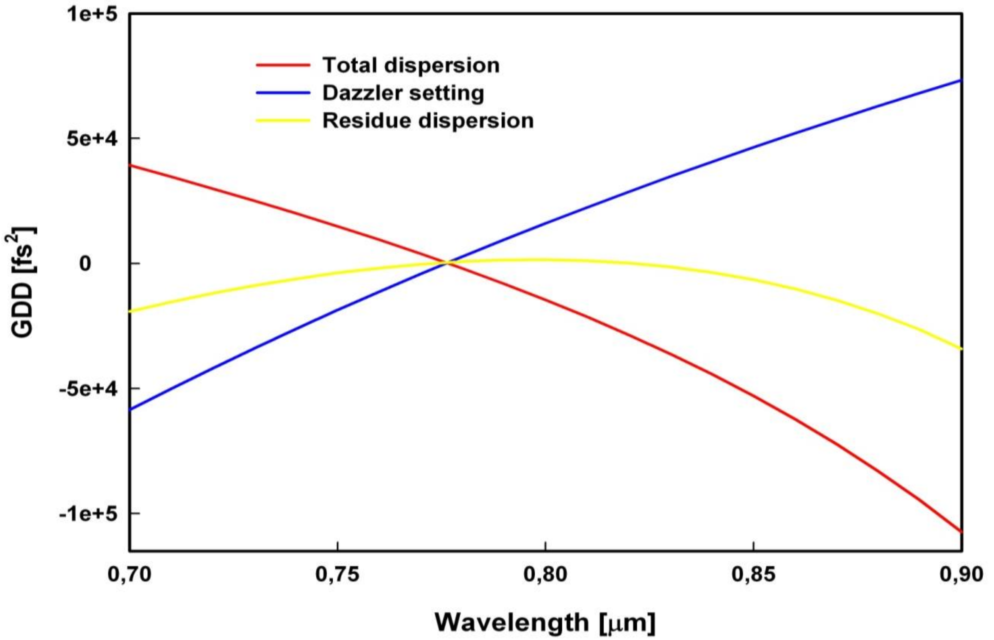


Acoustic-Optic Programmable Dispersive Filter for spectral amplitude and phase control

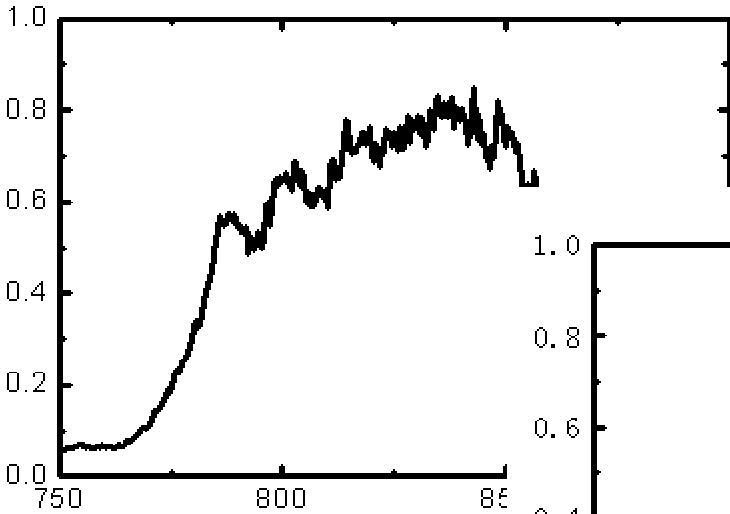
F. Verluise, V. Laude, Z. Cheng, Ch. Spielmann, and P. Tournois Opt. Lett. 25, 575 (2000)

High order dispersion compensation

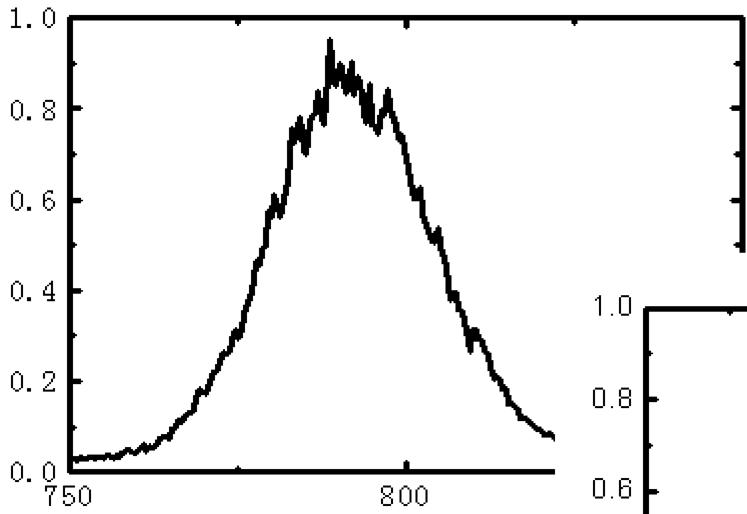




Spectra with shaping technique

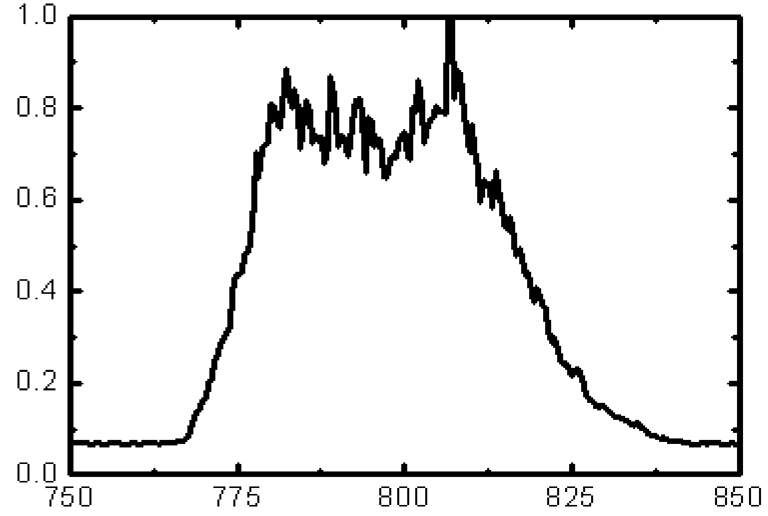


Seeding pulse

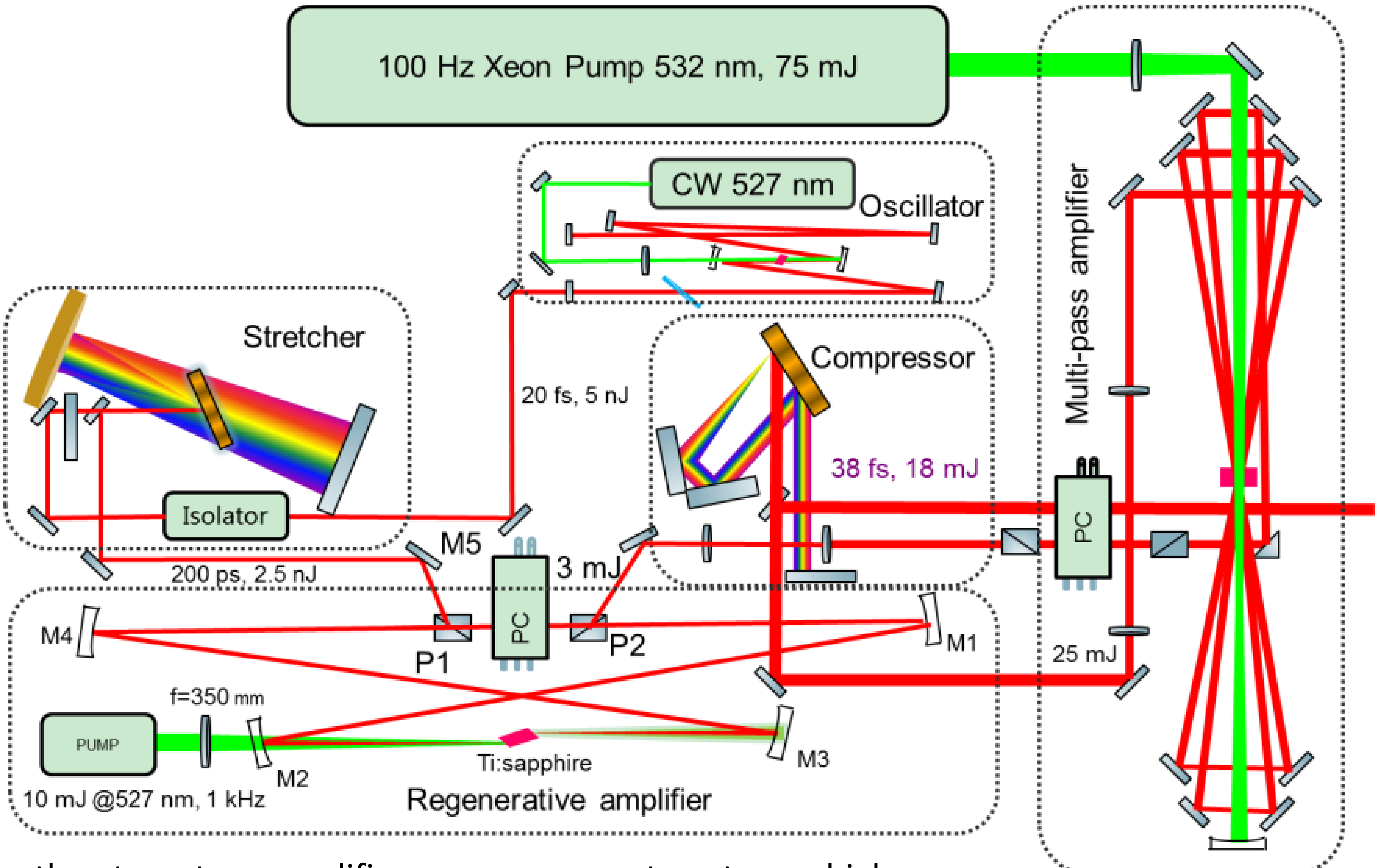


Amplified pulse wit
AOPDF work

Amplified pulse with
AOPDF work

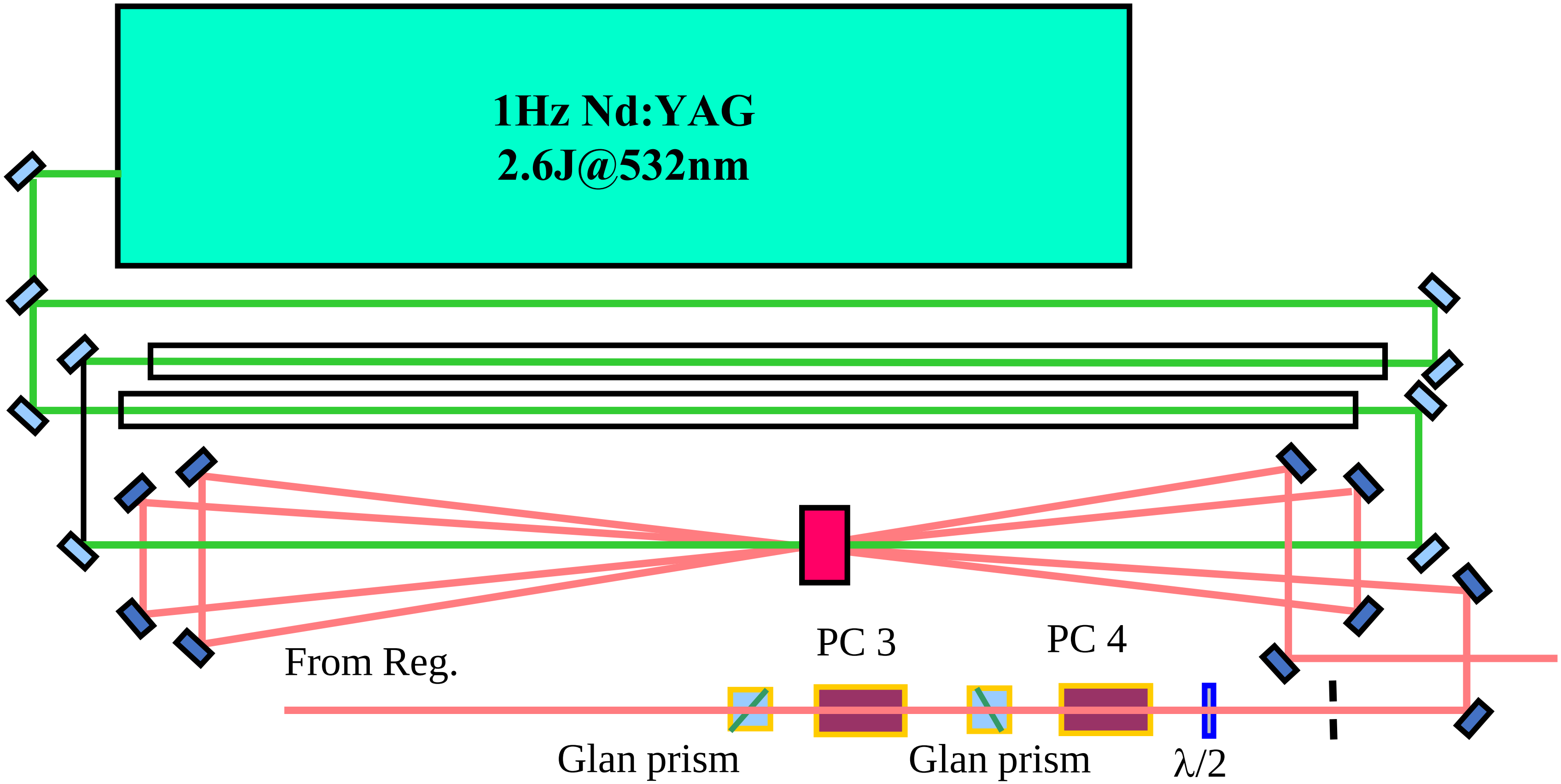


4. Amplify Chirped Pulse with two stages



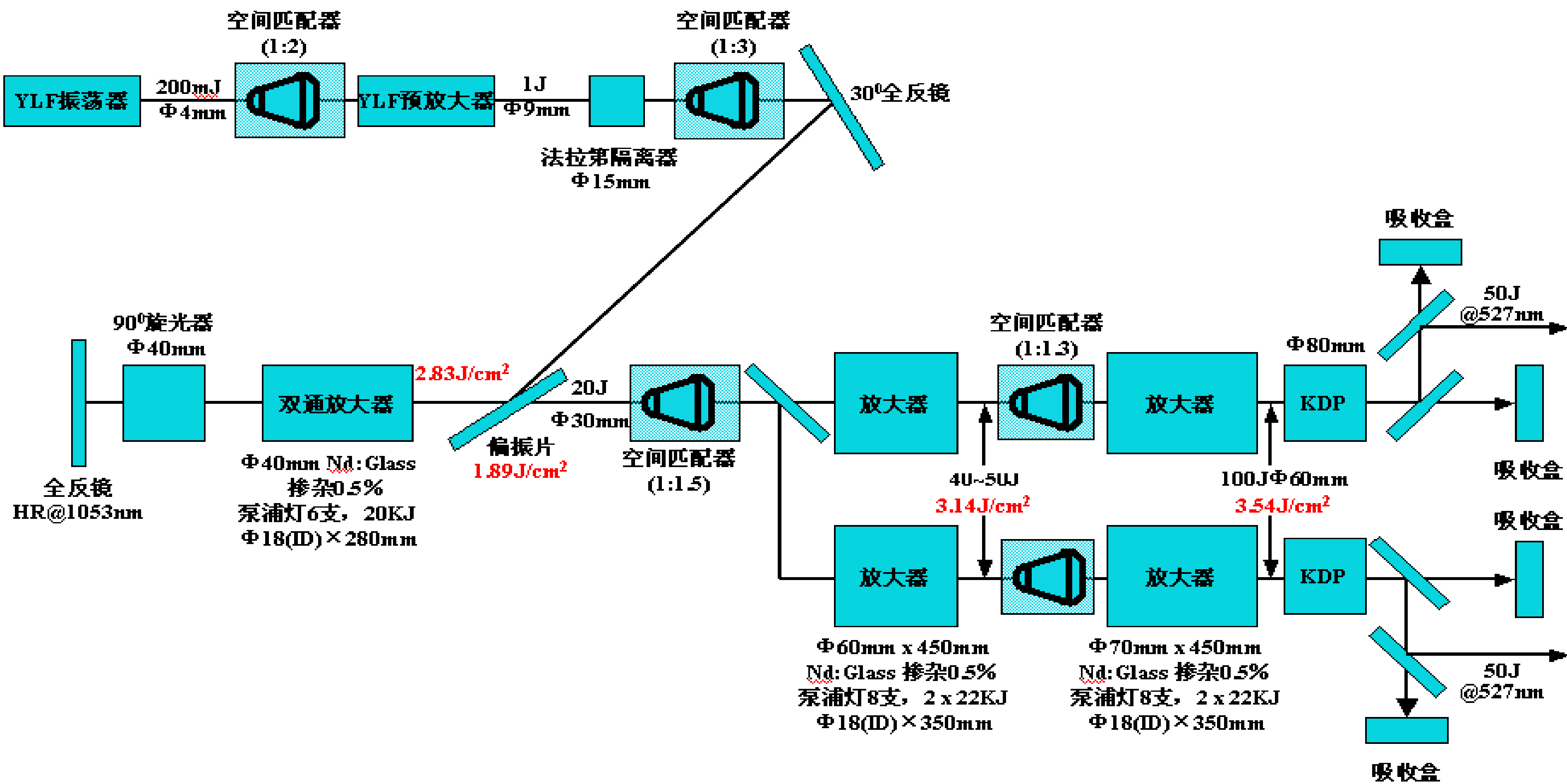
More than two stage amplifiers are necessary to get even higher energy

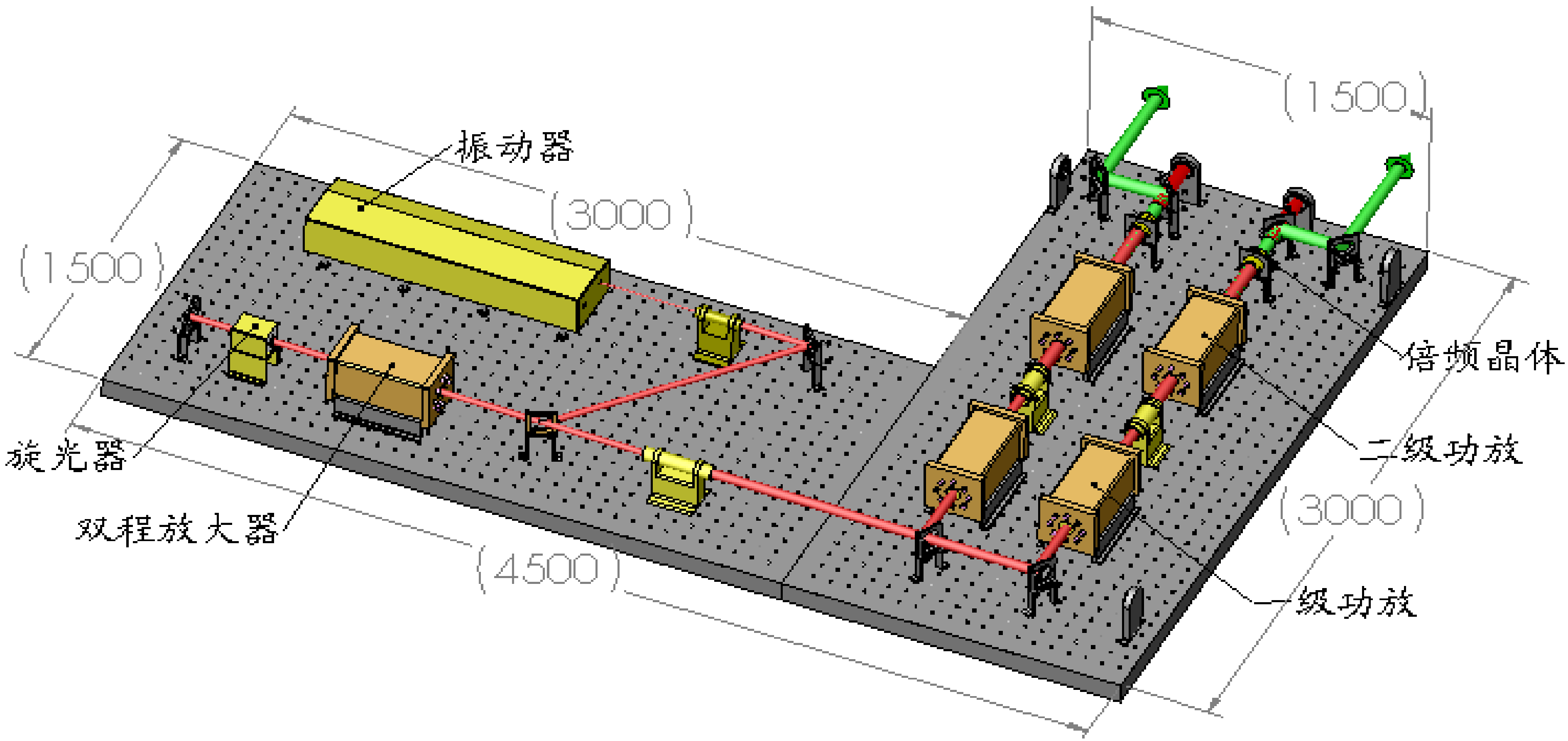
Multi-pass amplifier at 1Hz



Because of limitation by pump laser and thermal effect, the repetition rate should be reduced for high energy goal. With 2.6J pump laser energy, amplified laser of 700mJ was obtained.

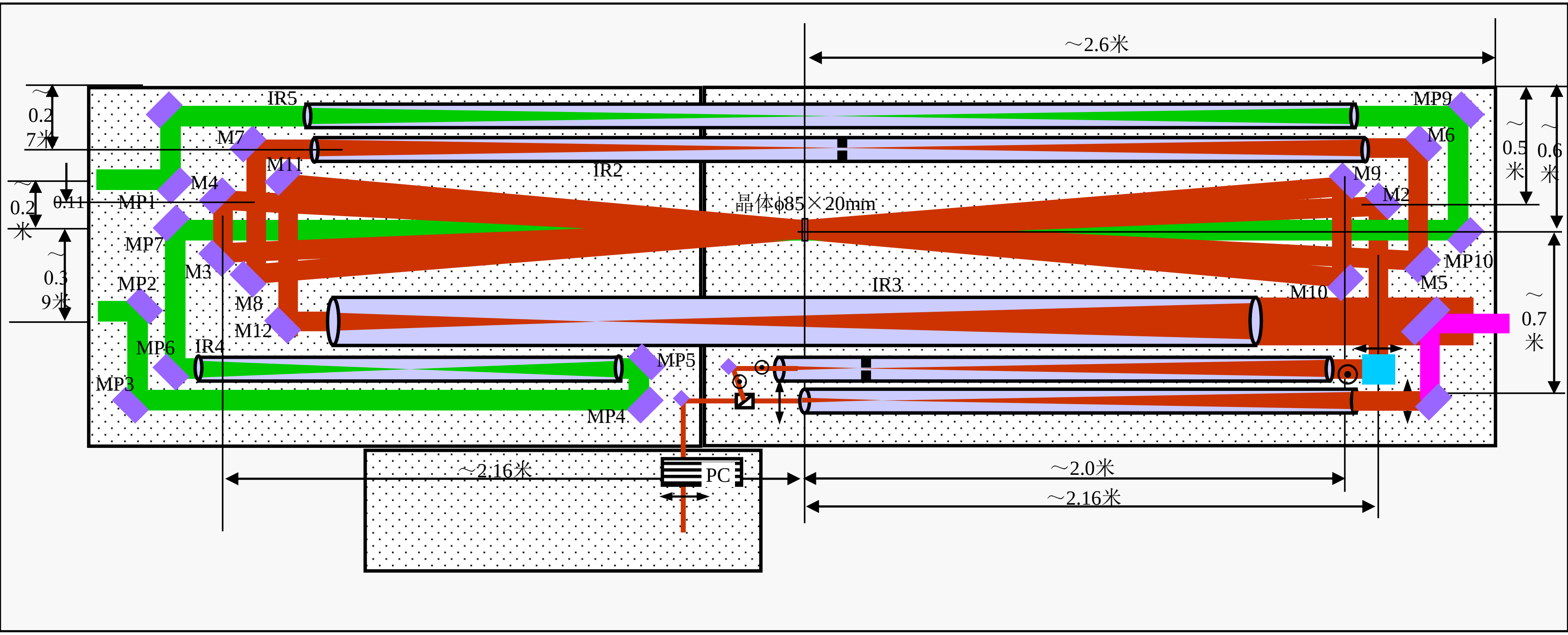
Design of high energy pump laser: 100J SHG Nd:glass laser




振动器
(3000)
(1500)
(1500)
旋光器
双程放大器
(4500)
倍频晶体
二级功放
(3000)
一级功放

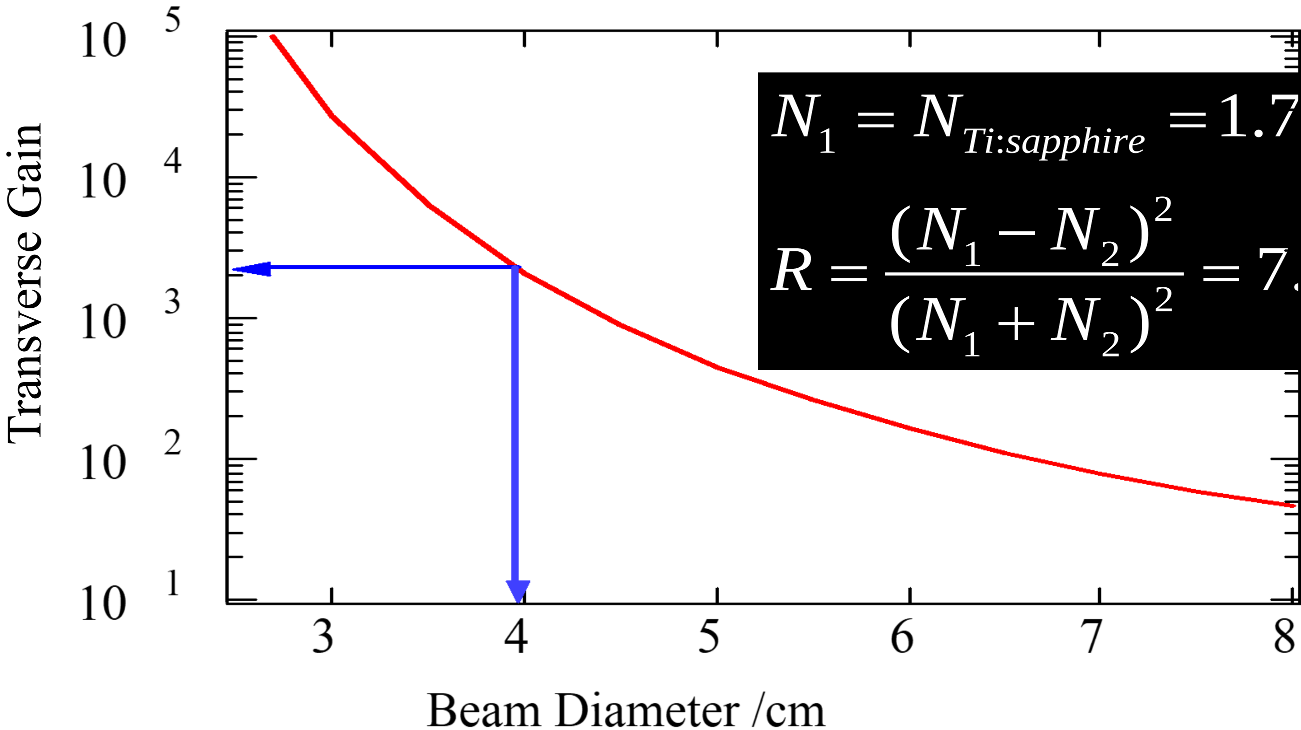
Pump:527nm Nd:glass laser
Energy:100J

Boost Amplifier



- ◆ **Pumped the final amplifier with 80J laser at 527nm, output laser energy was only 5J at initial experiment.**
- ◆ **The lower efficiency of amplification infer to the possible Amplified spontaneous emission(ASE)**

Eliminate ASE and PL with index match material

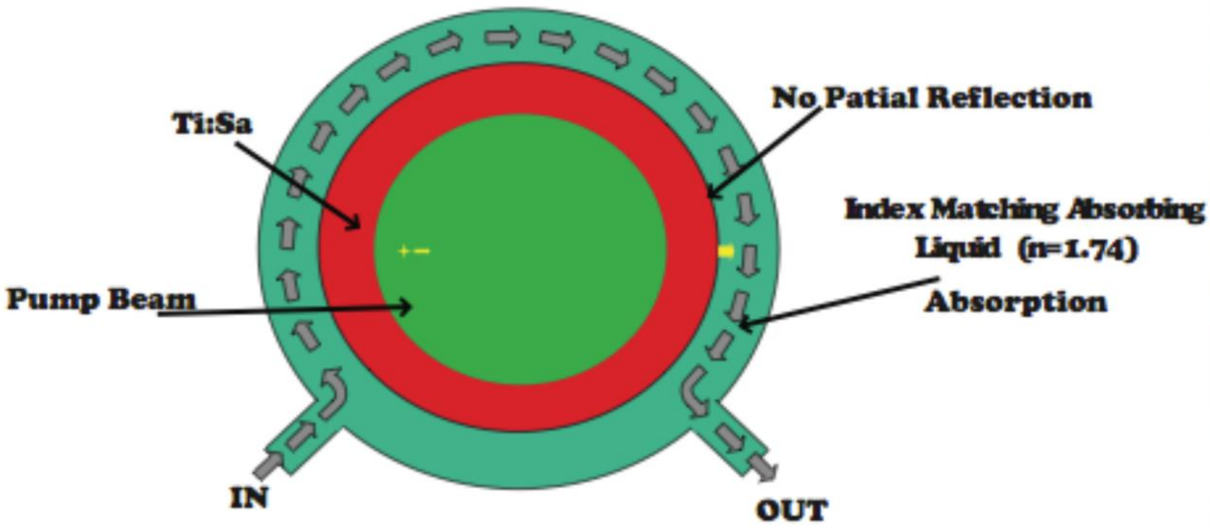


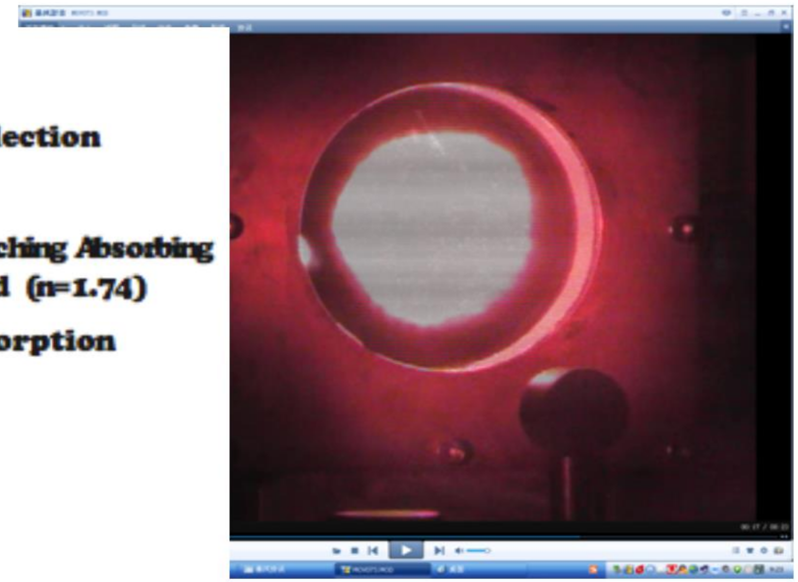
$$N_1 = N_{Ti:sapphire} = 1.76 \qquad N_2 = N_{air} = 1$$

$$R = \frac{(N_1 - N_2)^2}{(N_1 + N_2)^2} = 7.6\% \qquad G = 1/R = 13$$

- **Using thermoplastic (Cargille Laboratories, Inc.) material can well eliminate the effect.**
- **Amplified energy of 20J was obtained finally, increase from 5J to 20J**

Suppression of parasitic lasing by using index match material

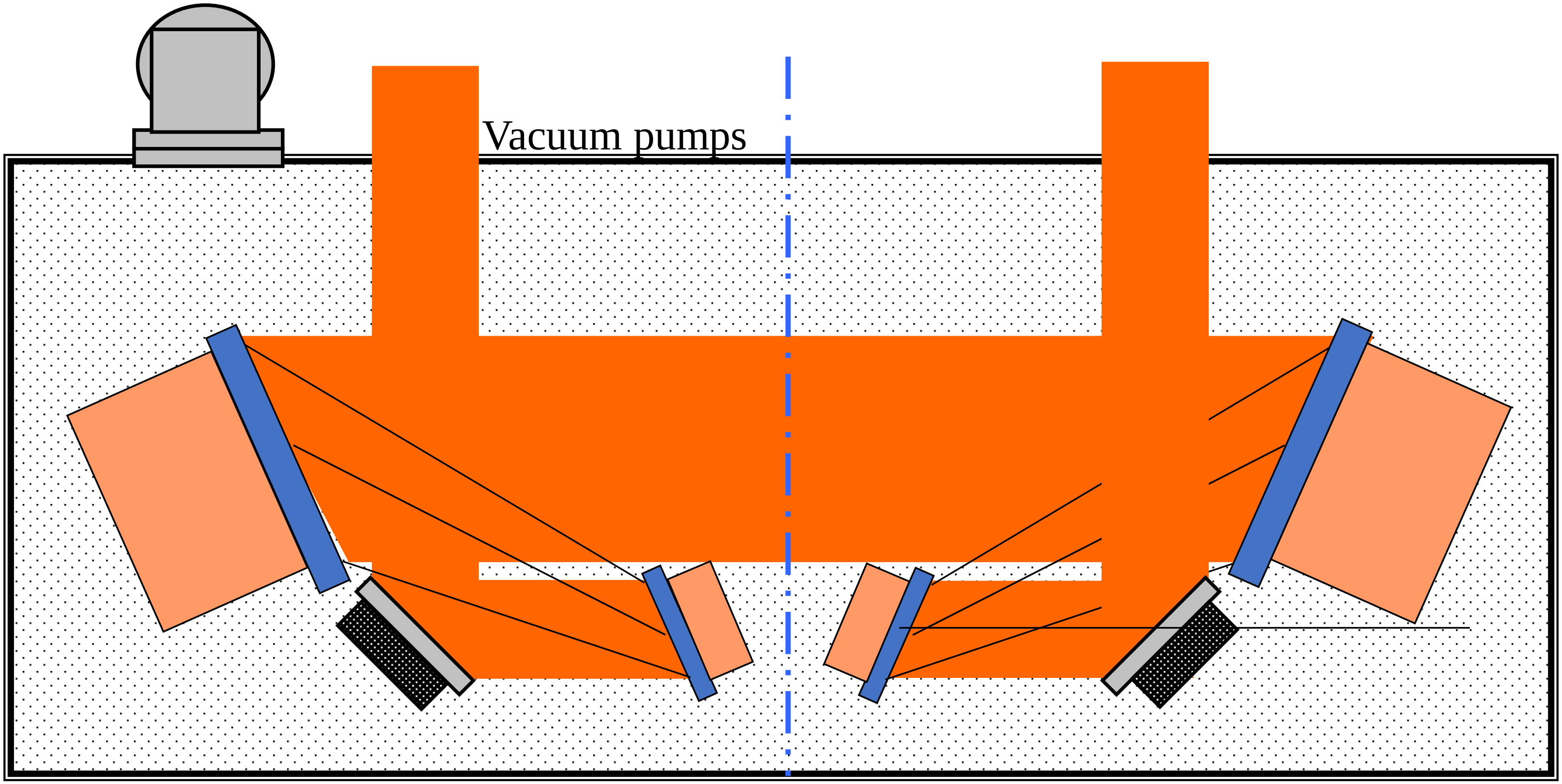




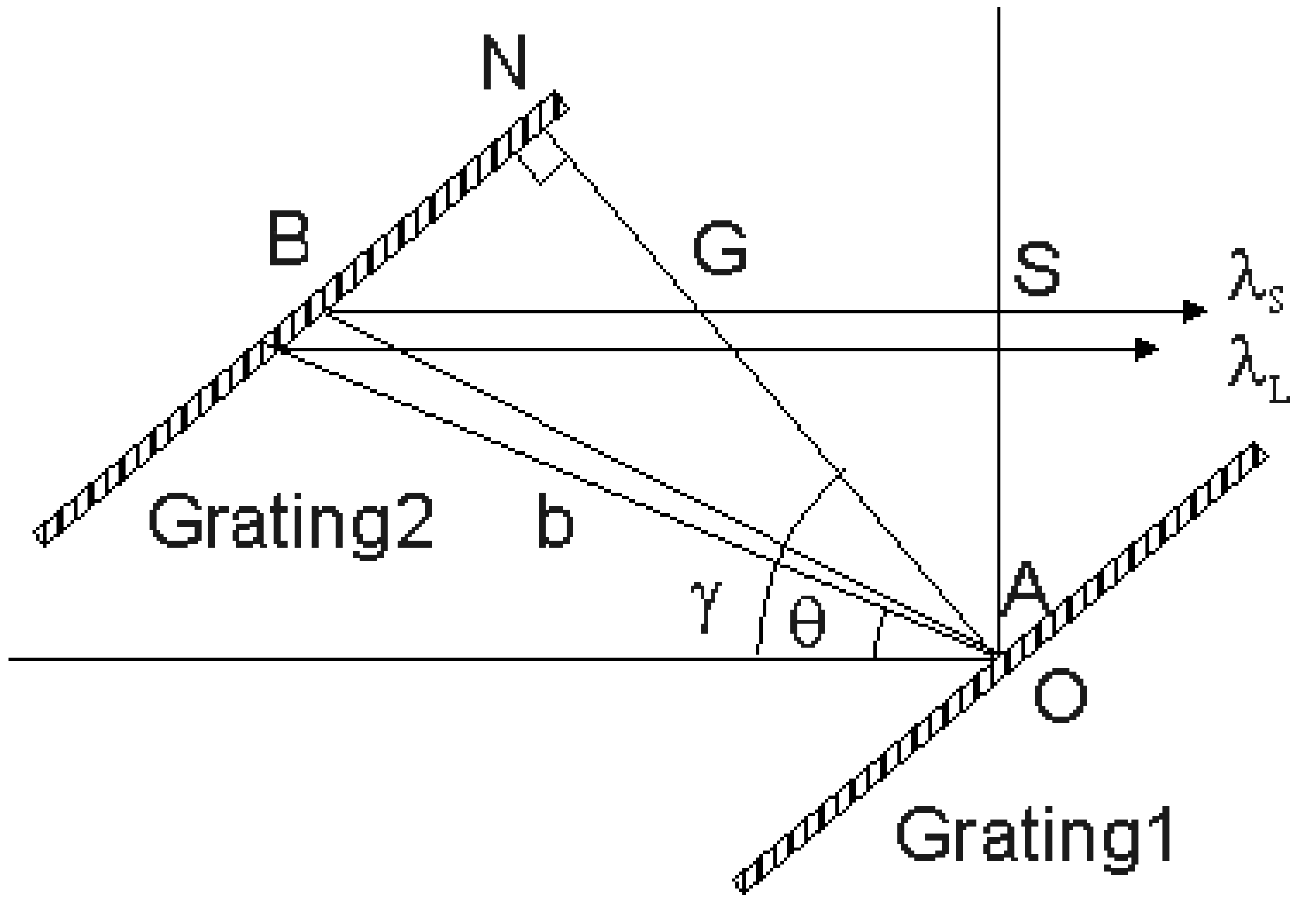
With a Ti:sapphire crystal of ƒ80X40mm in size, 46.8J laser energy was obtained by eliminate the parasitic lasing and enlarge the beam diameter to 70mm to fit the optimized energy flux of about 3.1J/cm^2. For save operation, we remained at a median efficiency.

Compressor- Compensate dispersion for high peak power

Layout of vacuum compressor

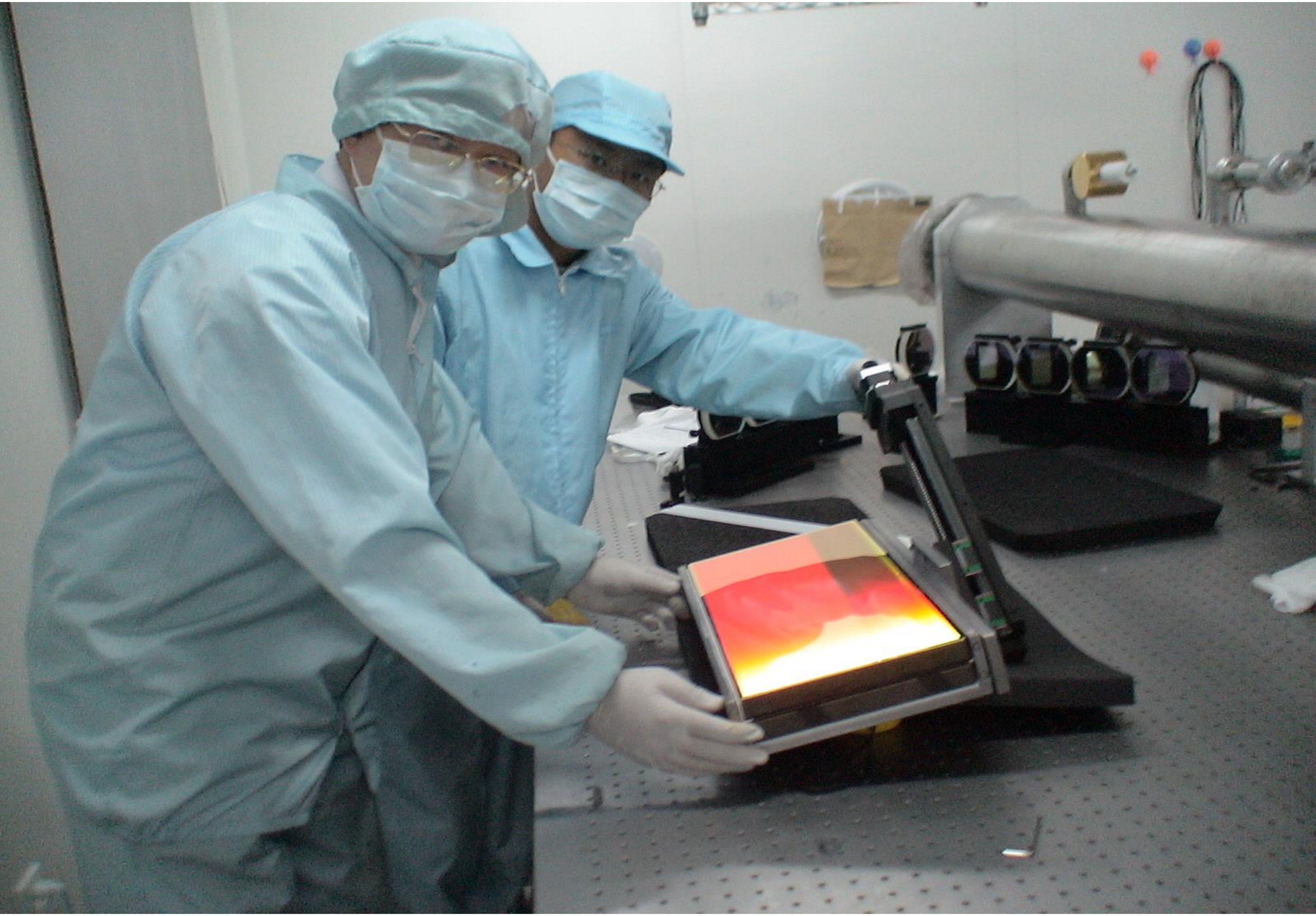


Space size of the chamber：900×700mm,
Incident angle: 24 degree, diffractive angle: 51degree
E.Treacy equation(1969) : the dispersion is opposite to stretcher

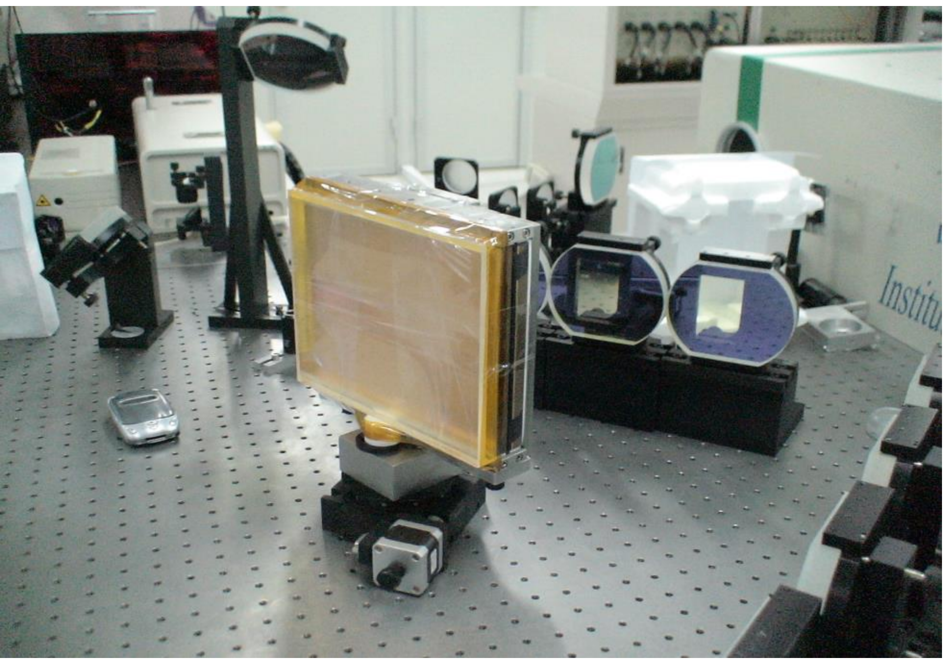


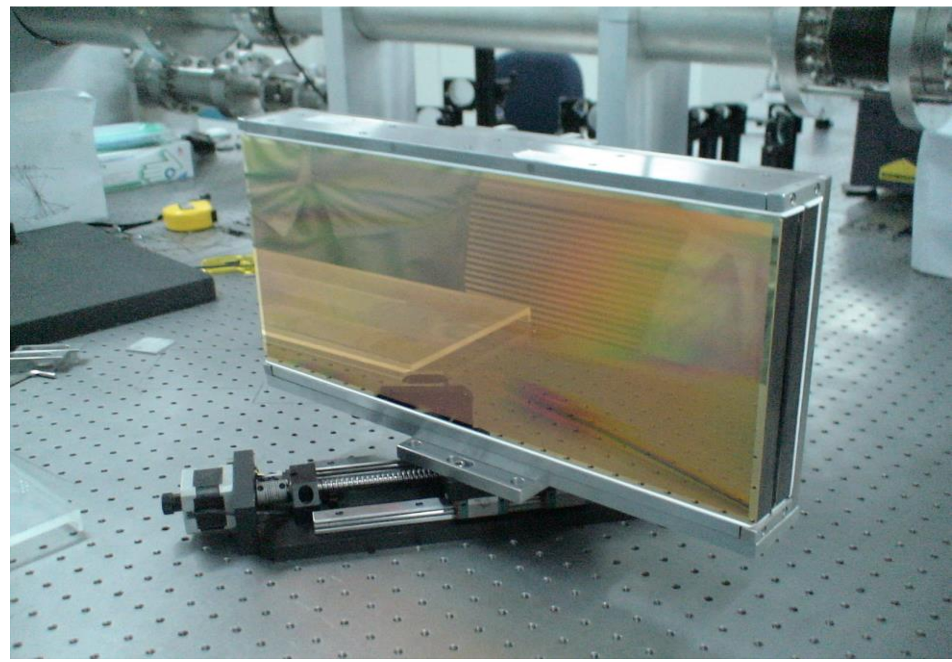
$$\varphi = \frac{\omega}{c} b(1 + \cos\theta) - \frac{2\pi G}{d} \tan(\gamma - \theta)$$

E. B. Treacy, IEEE J. Quantum Electron. QE-5(9), 454~458(1969)

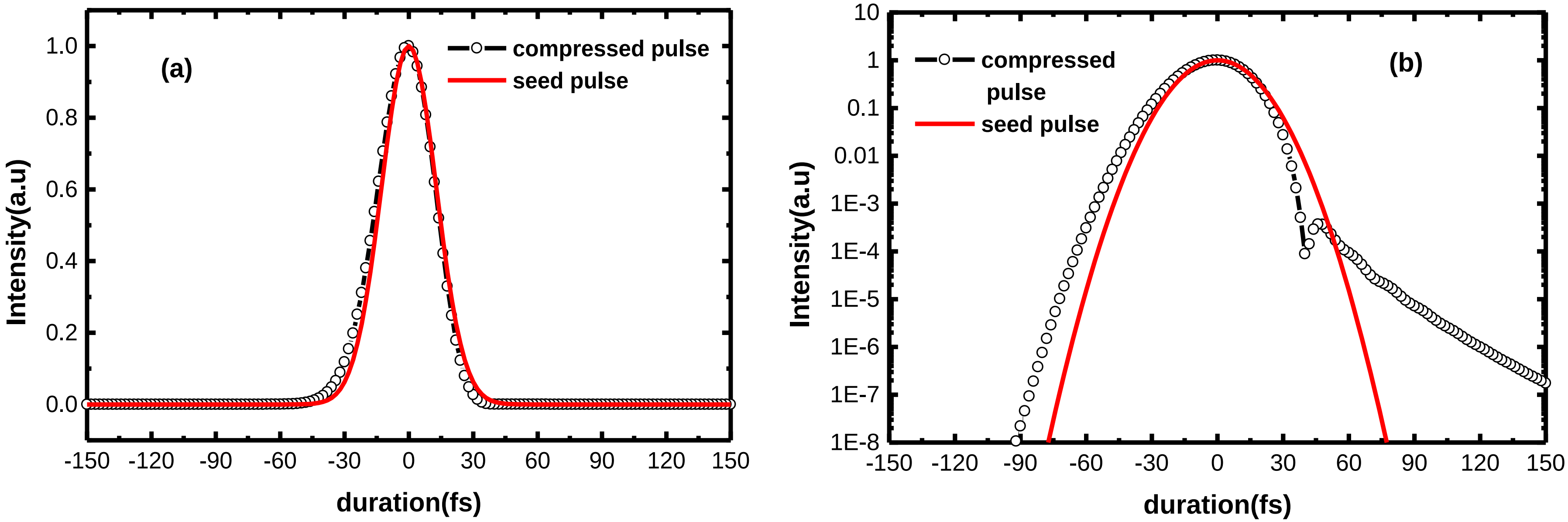


Gratings of compressor





Calculation for compressor



- **Grating groove of the compressor is 1480/mm**
- **The experiment shows the transmisstivity is larger than 60%, corresponding to the compressed energy is larger than 12J**
- **The calculation shows the compressed pulse of less than 25 fs is possible. For 40fs compressed pulse, it corresponds to a peak power is higher than 300TW**

Enhancement on contrast ratio

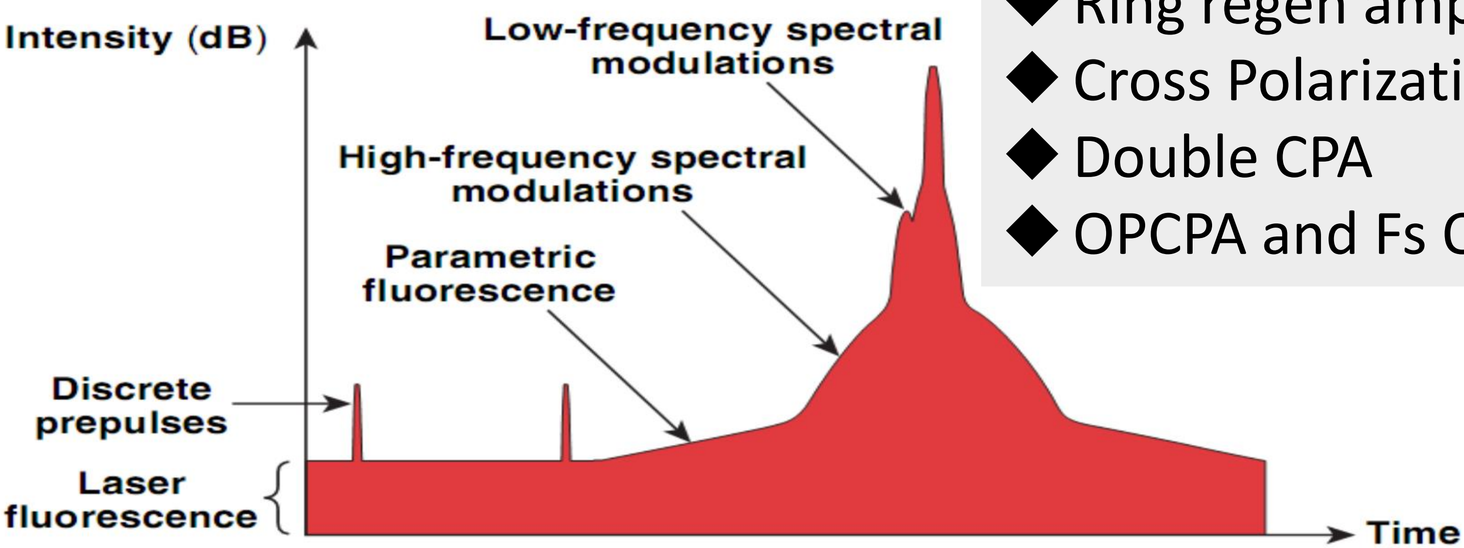
Questions on contrast ratio

Contrast Ratio (S/N): The intensity of main pulse to background.

Because of the pre-pulses, ASE and fluorescence, result in decreasing of S/N in amplification.

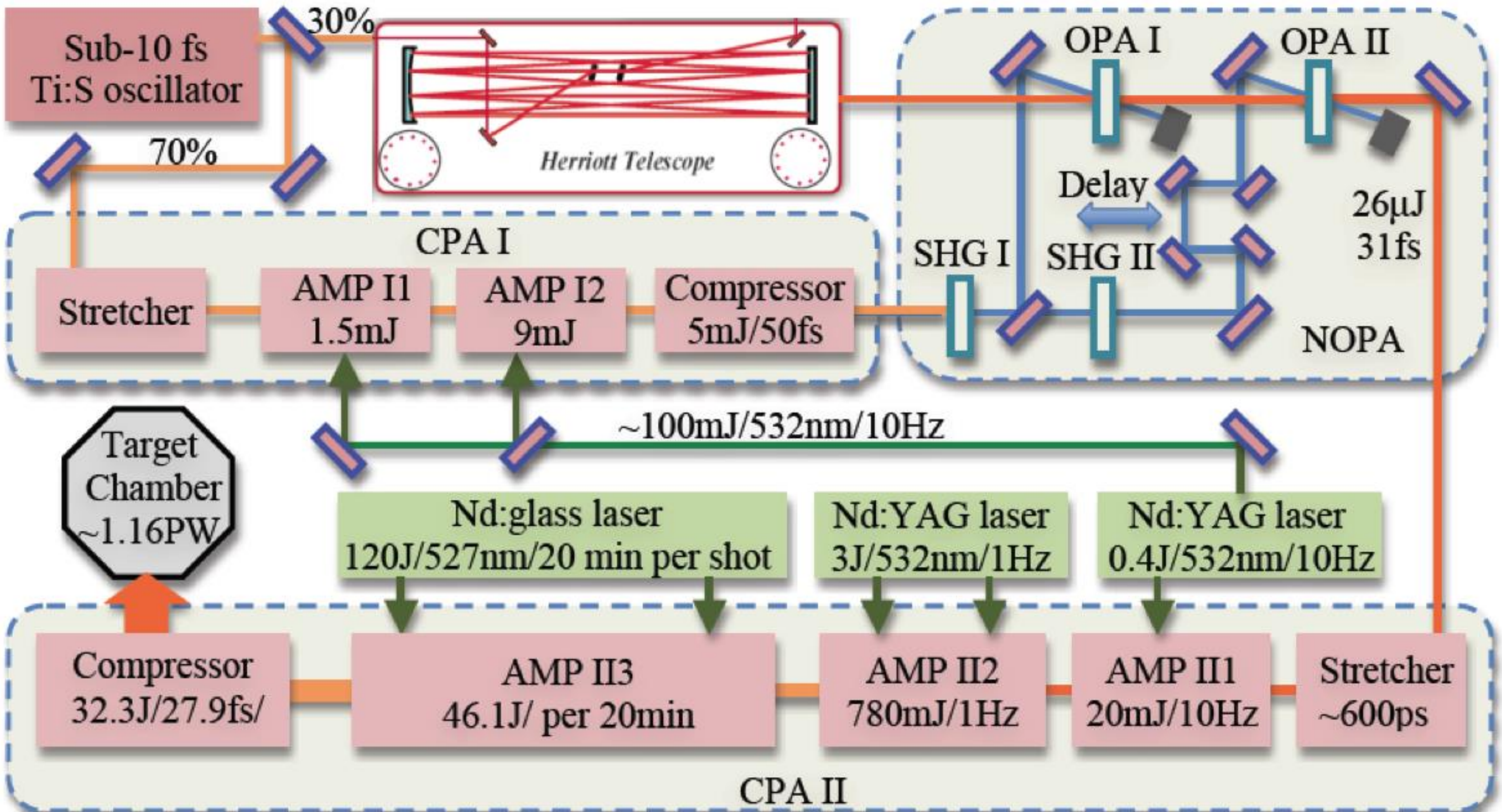
General techniques for improve S/N:

- More Pocket Cells
- Saturable Absorber
- Ring regen amplifier
- Cross Polarization Wave
- Double CPA
- OPCPA and Fs OPA



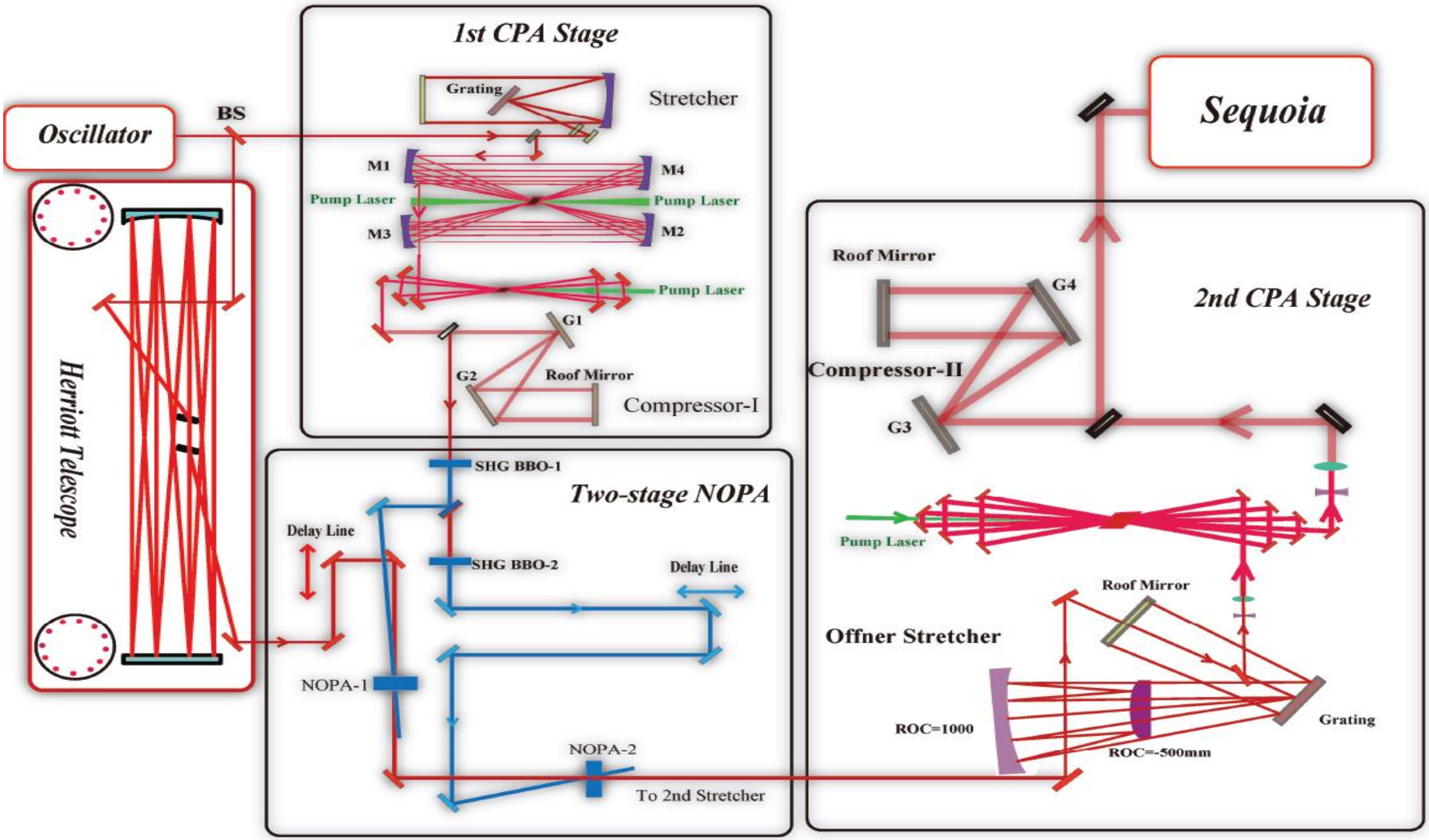
D. Umstadter, Phys. Plasmas **8**, 1774 (2001)

System Design for high contrast ratio

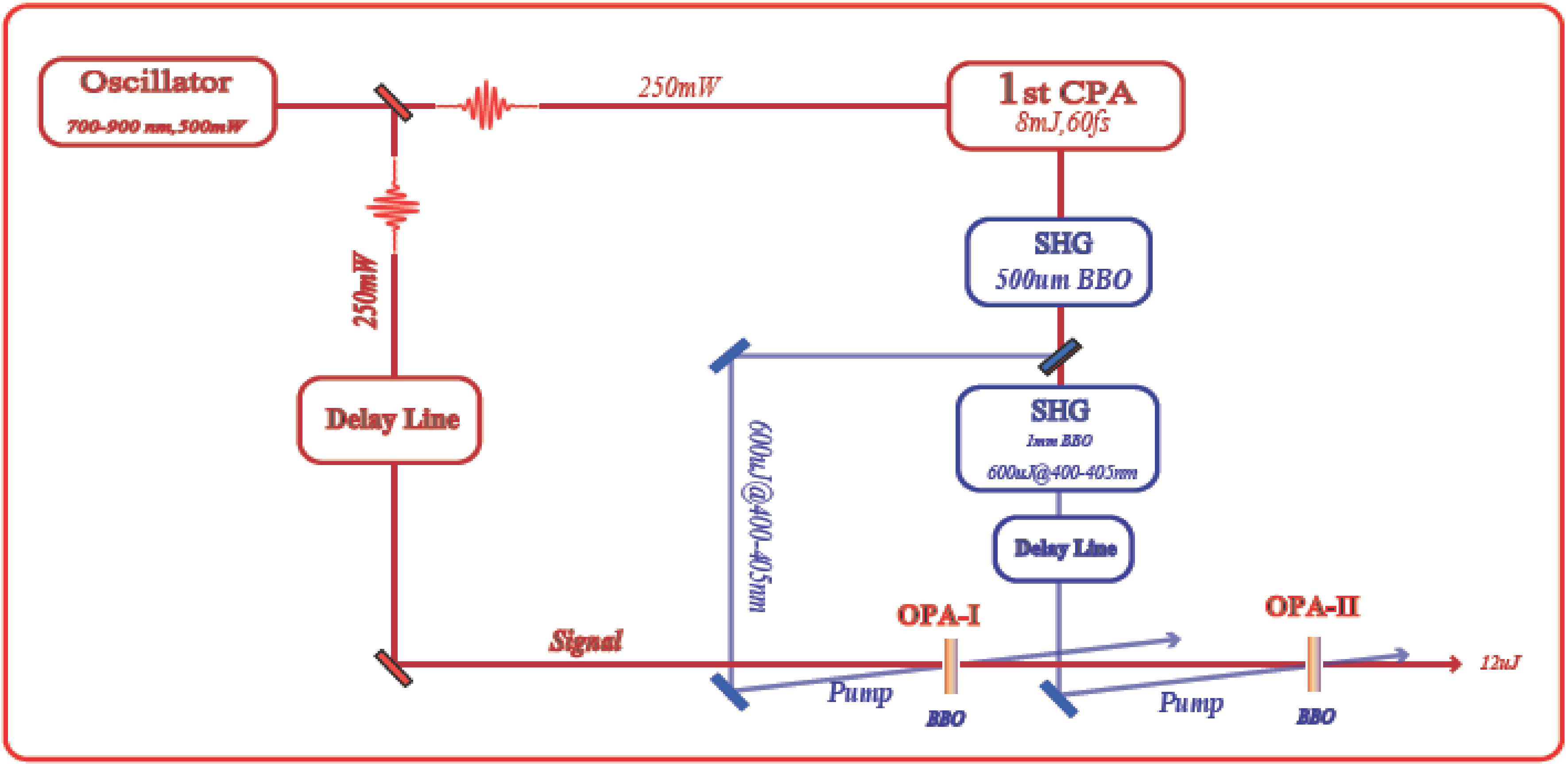


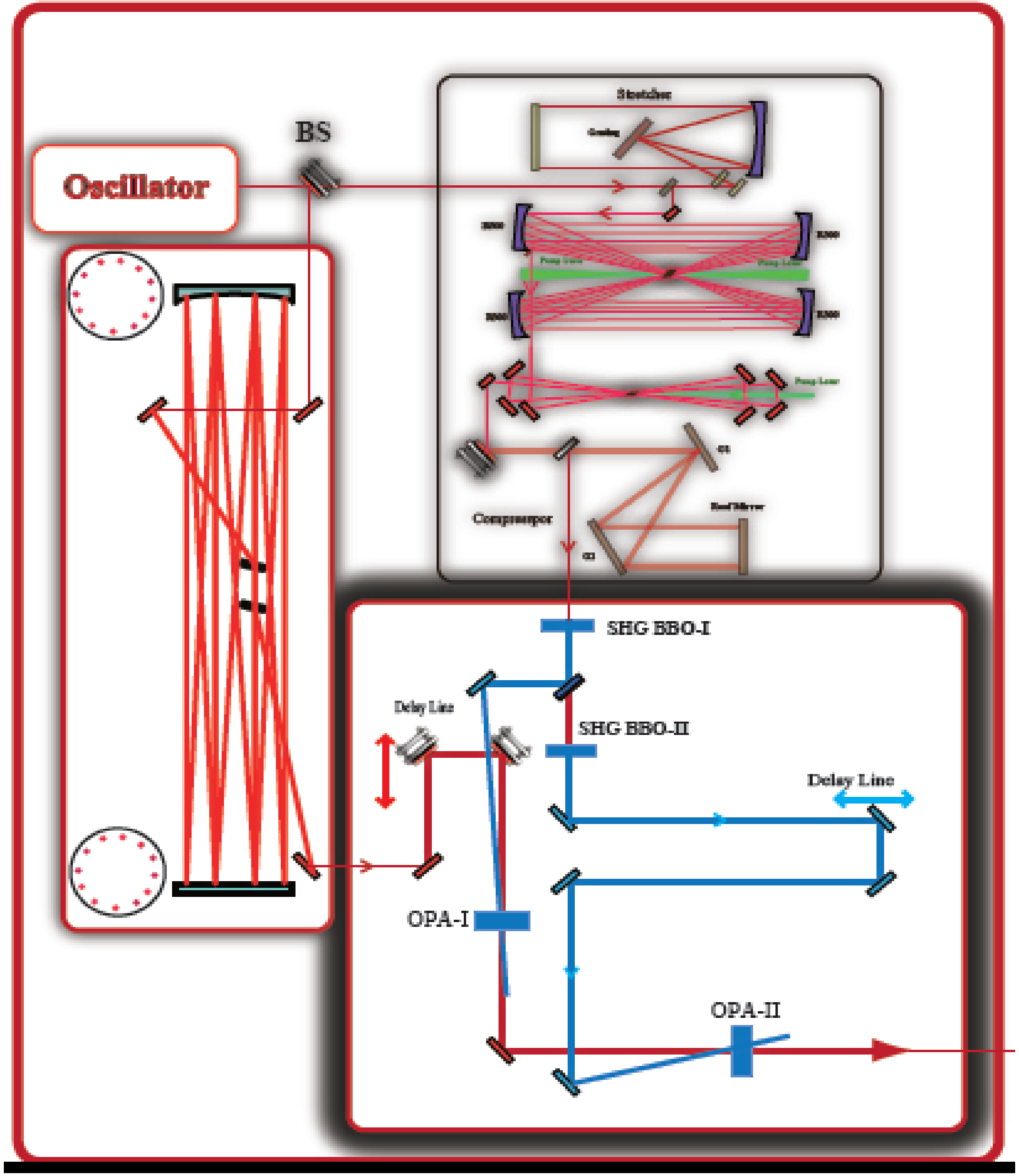
Doubled CPA+fs OPA

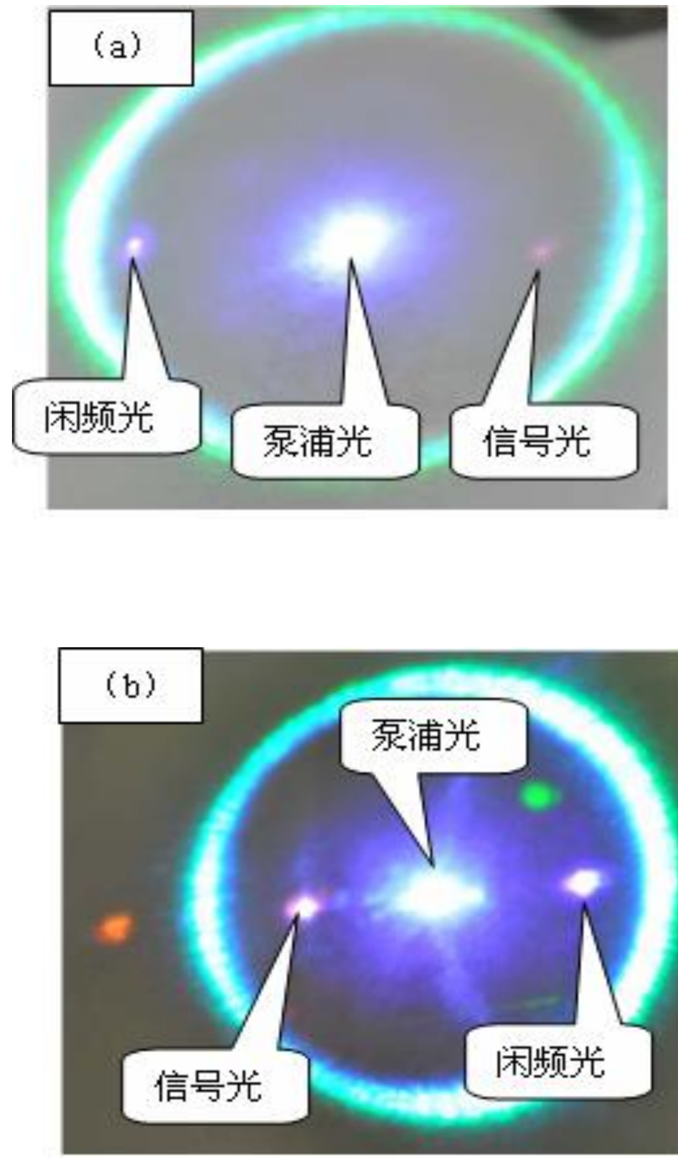
Non-Collinear OPA (NOPA)



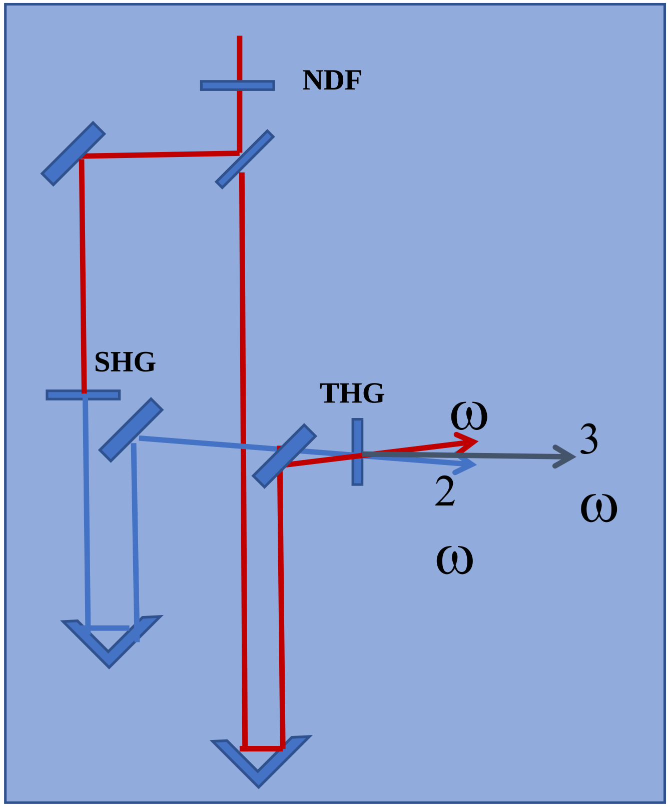
A simple descriptions on NOPA

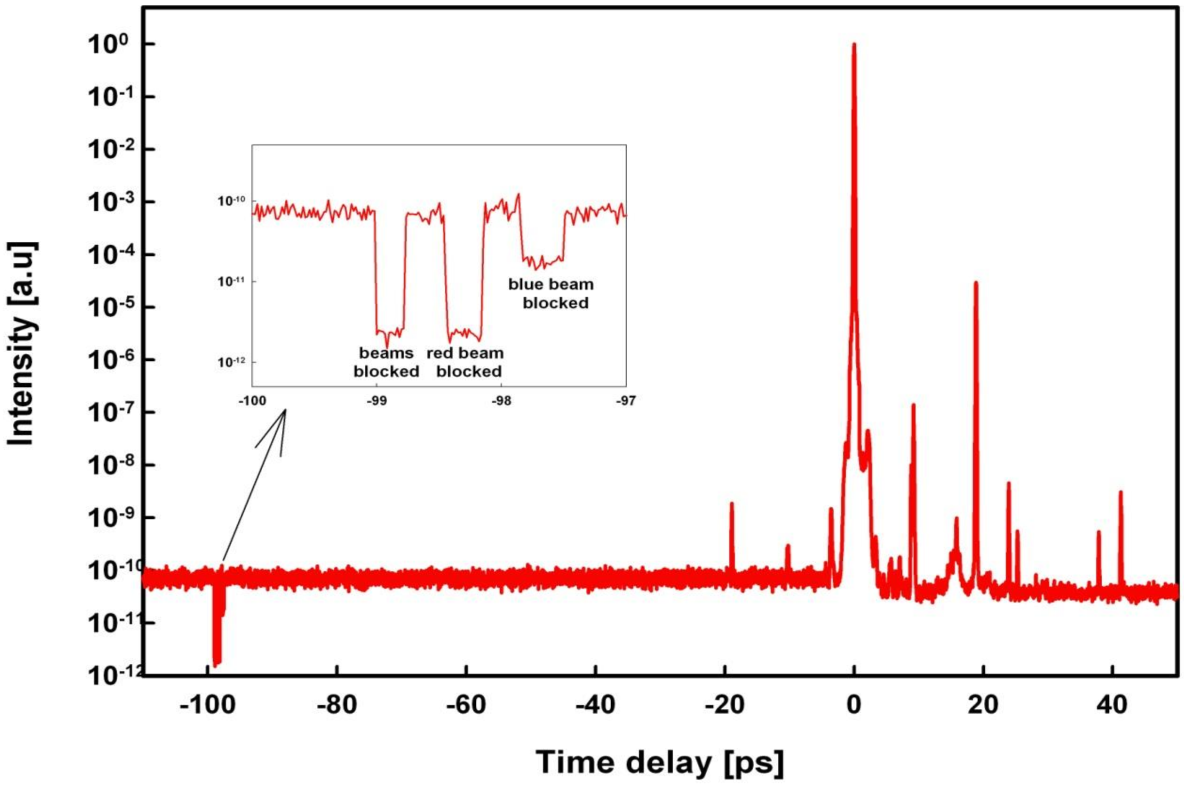



Oscillator
BS
Stretcher
Compressor
SHG BBO-I
Delay Line
SHG BBO-II
Delay Line
OPA-I
OPA-II

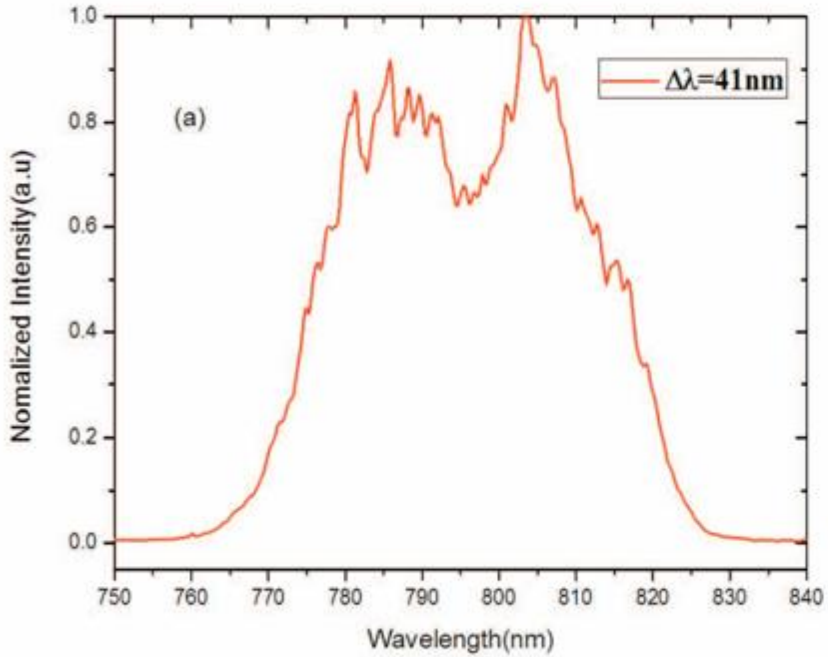

(a)
闲频光
泵浦光
信号光
(b)
泵浦光
信号光
闲频光

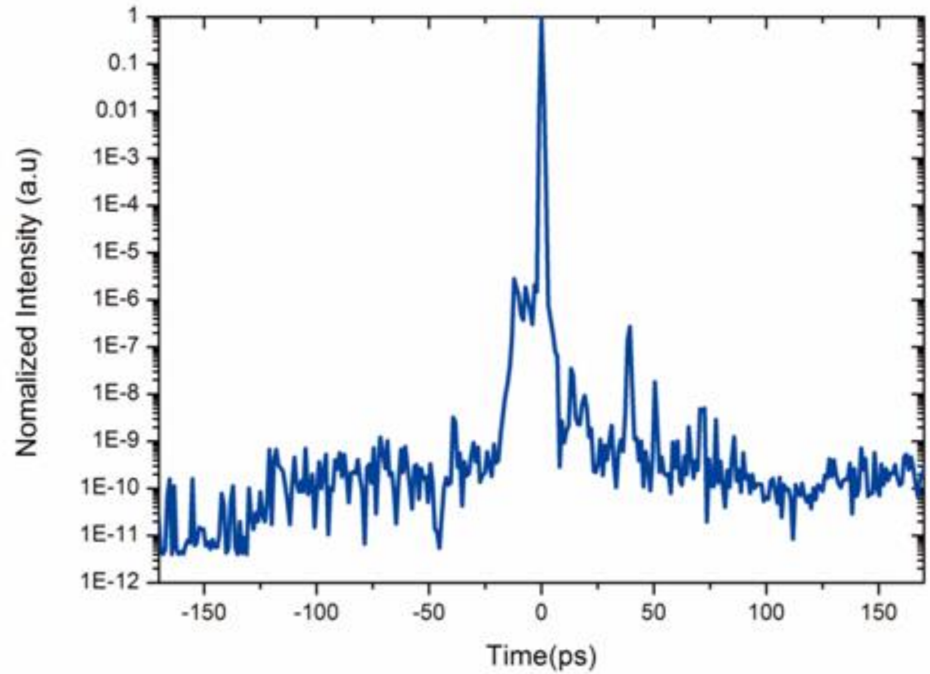
Measurement of Contrast Ratio Third cross-correlator





Measurement of contrast ratio



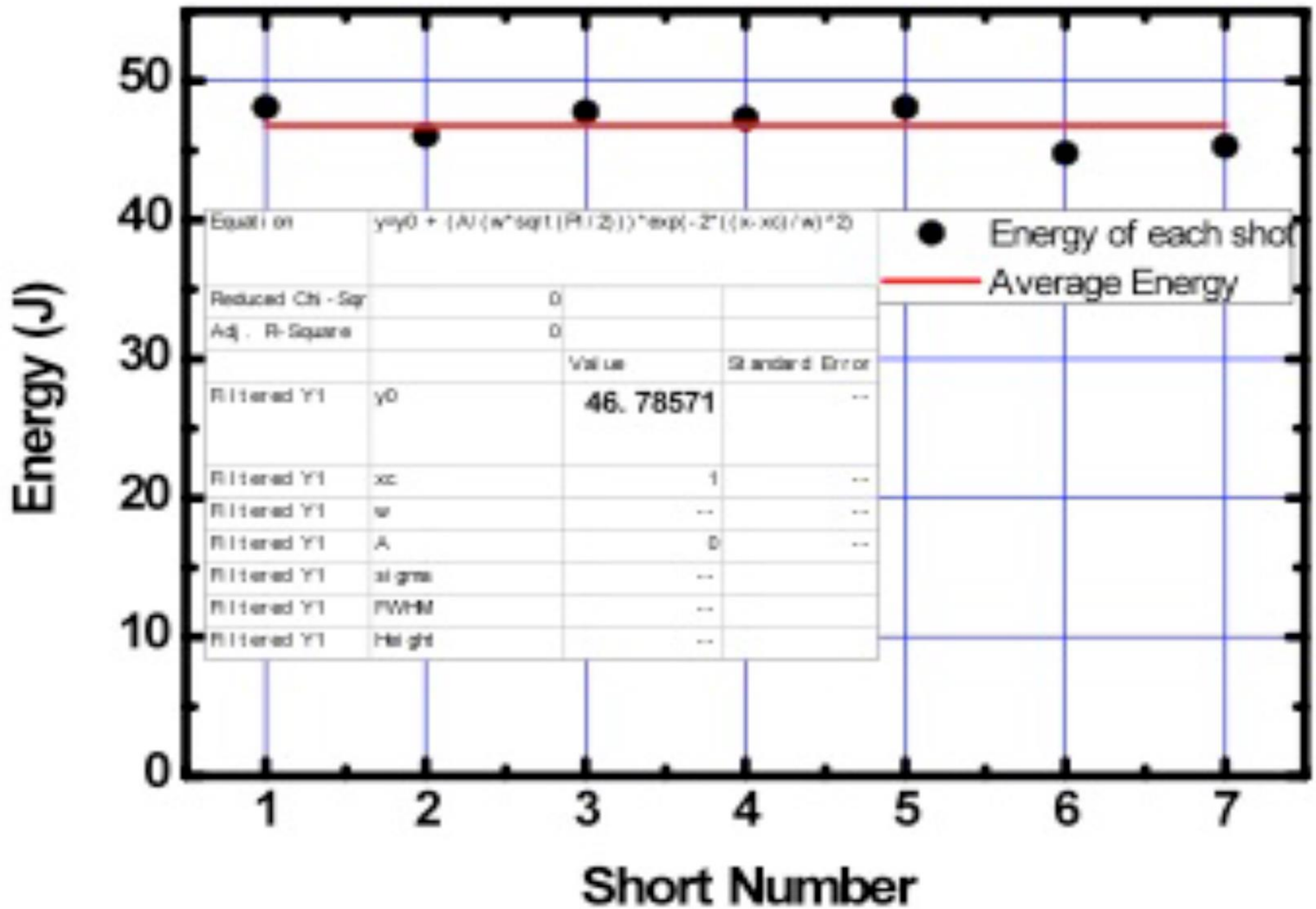


◆With two stage OPA pumped by the SHG of 800nm amplified laser from CPA I, signal energy up to 26μJ was obtained.

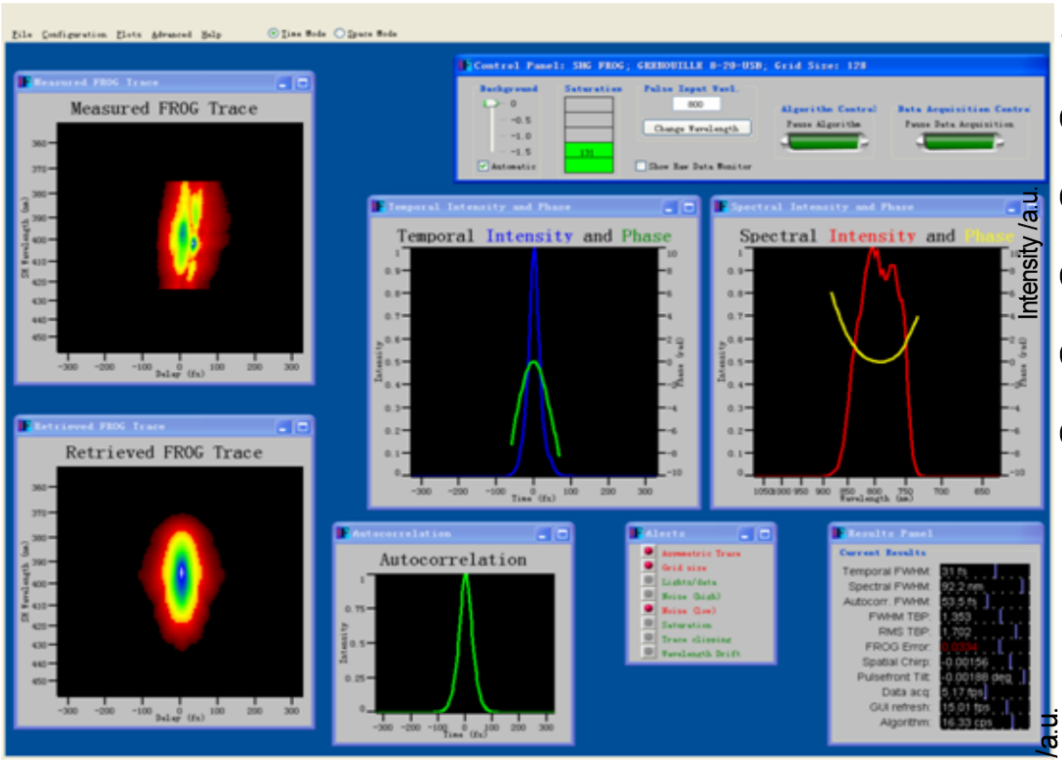
◆Measurement of third-order cross correlation shows the contrast ratio up to 10^{10} in temporal scale of 100ps.

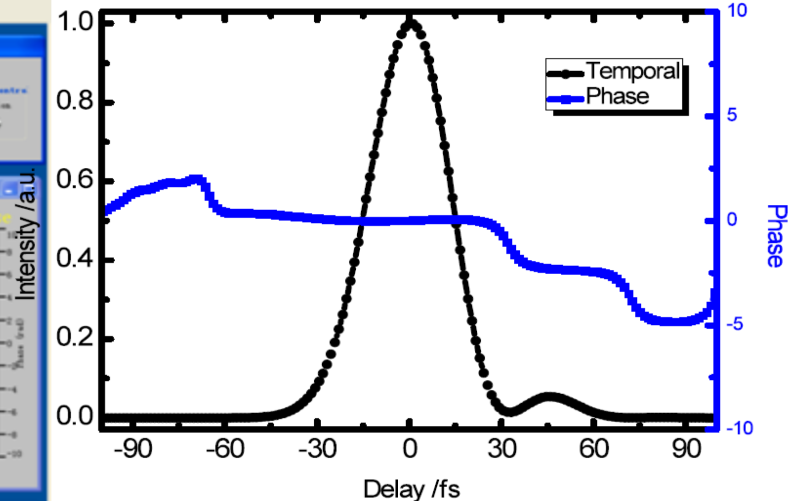
◆The FWHM spectral width is 41 nm, supports a recompressed pulse of shorter than 30fs---**Opt. Lett. 35, 3096(2010)**

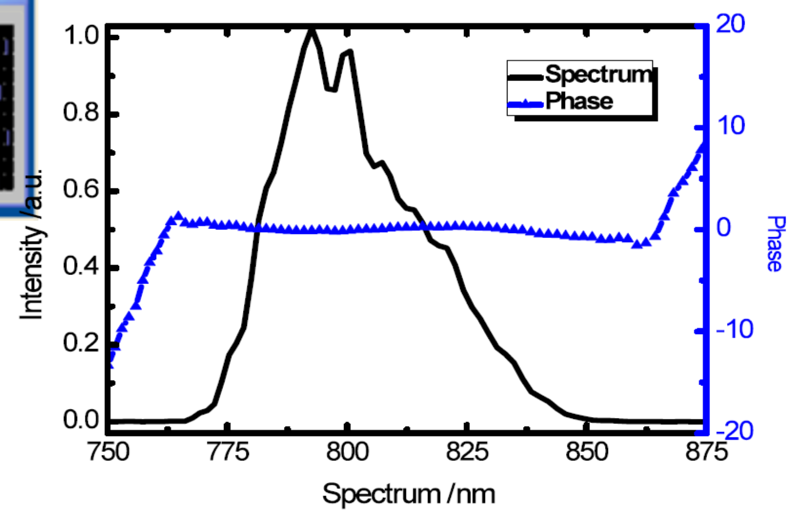
Laser shot energy per 20 mins



Laser measurement with FROG







Measured results by SHG-FROG

FWHM spectral width: ~41 nm.

Pulse duration: ~27.9fs,

⇨1.16PW

eXtreme Light (XL) III Facility

Progresses step of laser facility at IoP in last decade:

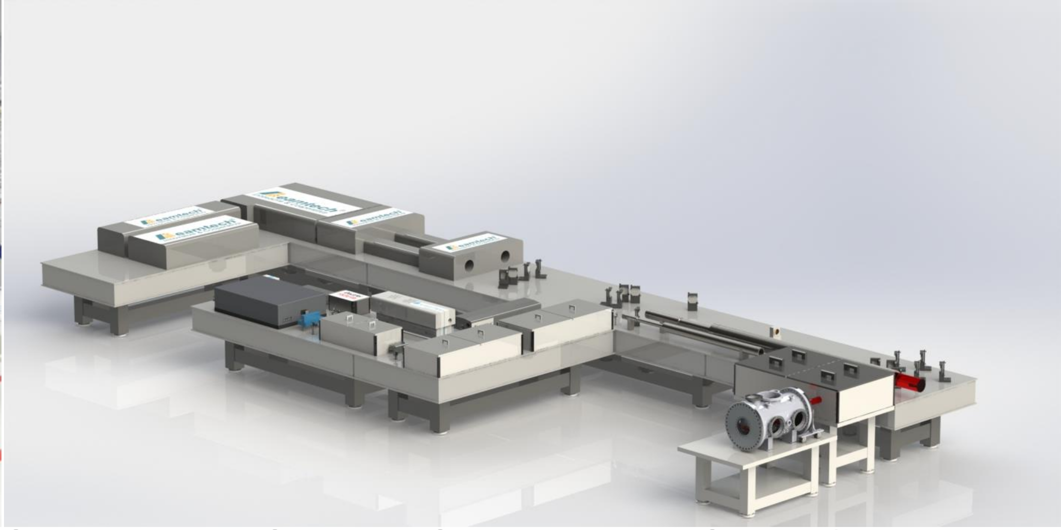
350TW@2007,

750TW@2008,

1.16PW@2011. contrast： ~10^{10}

Opt Lett, 3096(2010) & 3194(2011)

Repetition rate: Singe shot per 20 mins.



Electron and proton acceleration have been realized.

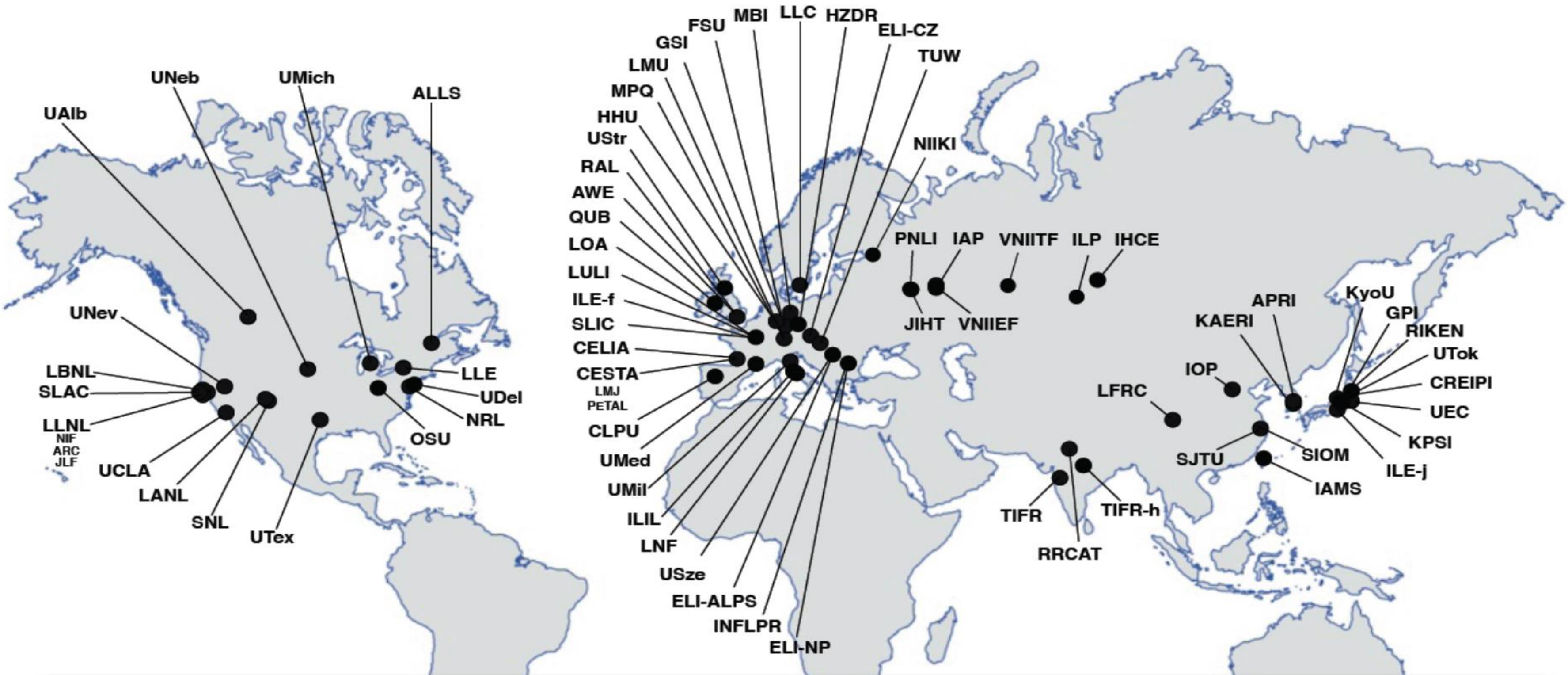
Typical PW laser facilities in the world

Some femtosecond Ultrahigh Intensity Laser Facilities in the World

- ◆1999. M. D. Perry, 1.4PW, OL 24, 160
- ◆2003, M. Aoyama *et al.*, 0.85PW/33fs, OL 28, 1594
- ◆2007, Z. Y. Wei *et al.*, 355TW/30fs, CLEO JWC2
- ◆2007, X. Liang *et al.*, 890TW/29fs, OE 15, 15335
- ◆2008, K. Ertel *et al.*, ~500TW, OE 16, 8039
- ◆2008, E. Gaul, 1.1PW/Hybrid, ICUIL
- ◆2010, J. H. Sung *et al.*, 1.0 PW, OL 35, 3021
- ◆2011, Z. Y. Wei *et al.*, 1.16PW, OL 36, 3194
- ◆2012, Tae Moon Jeong *et al.*, 1.5PW, OE 20, 10807
- ◆2015, X. Liang *et al.*, for 5PW, OL 40, 5011
- ◆2017, SIOM, China, 10PW

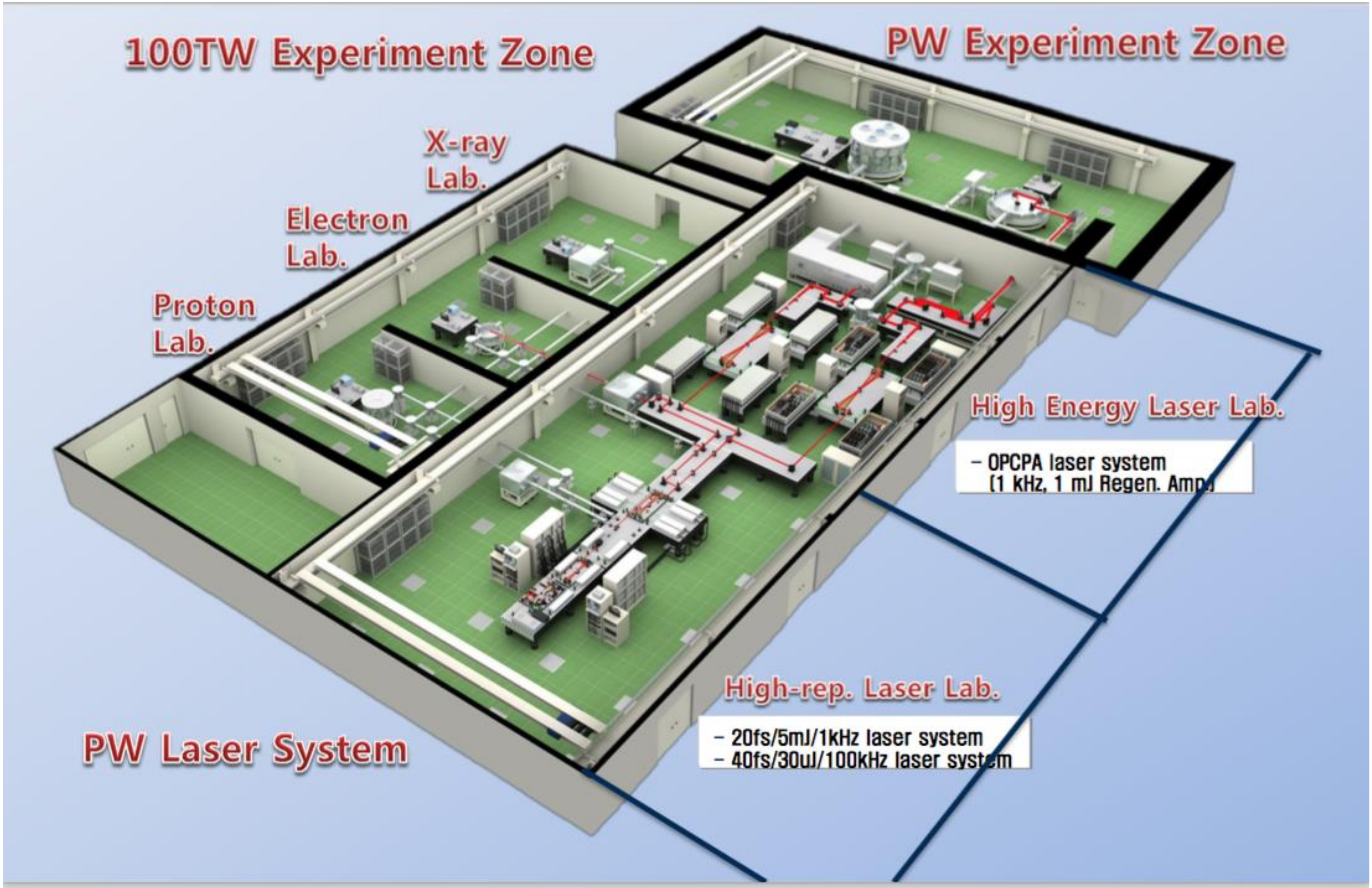
……

2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities



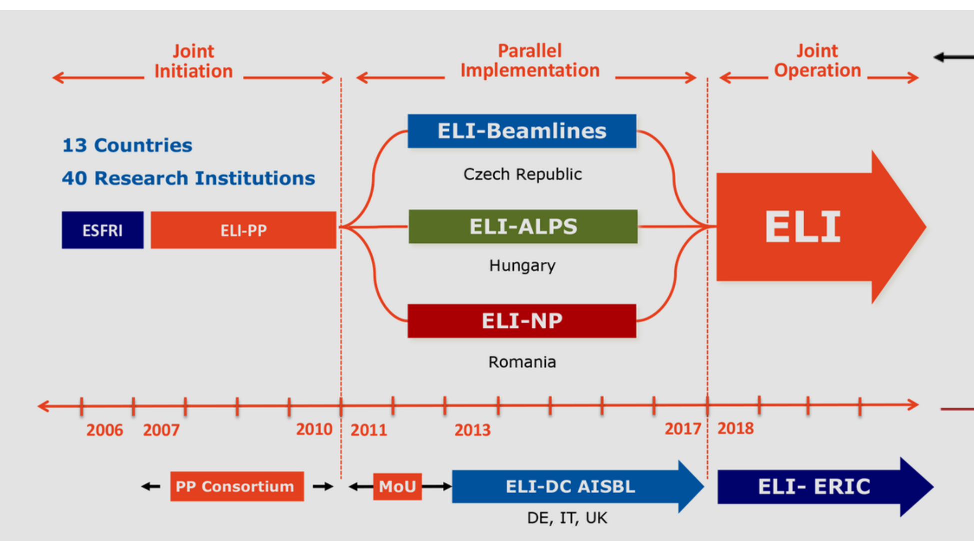
- the total peak power of all the CPA systems operating today is ~11.5 PW
- by the end of 2015 planned CPA projects will bring the total to ~127 PWs
- these CPA projects represent ~$4.3B of effort by ~1600 people (no NIF or LMJ)
- these estimates do not include Exawatt scale projects currently being planned

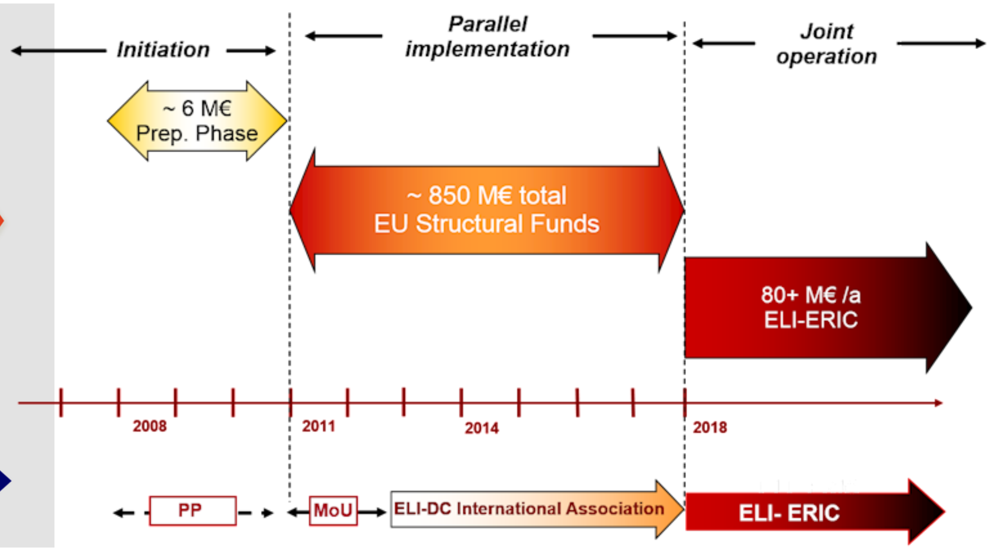

National user facility
for the user in femto science and techology
Laser systems in UQBF
• Low-power laser (< 1 TW) : Pulse width (20~100fs), pulse energy (nJ~mJ), repetition rate (10, 1kHz, etc)
• Mid-power laser (< 100 TW) : Pulse width (30fs~10ps), pulse energy (~3J), repetition rate (10Hz)
• High power laser (PW) : Pulse width (30fs~10ps), pulse energy(~30J), repetition rate (0.1Hz)
• The component of UQBF (10,257.9 m^2): Research building, conference hall, seminar room and guest house



100TW Experiment Zone
PW Experiment Zone
X-ray Lab.
Electron Lab.
Proton Lab.
High Energy Laser Lab.
- OPCPA laser system
(1 kHz, 1 mJ Regen. Amp)
High-rep. Laser Lab.
- 20fs/5mJ/1kHz laser system
- 40fs/30uJ/100kHz laser system
PW Laser System

ELI-The most powerful laser in future

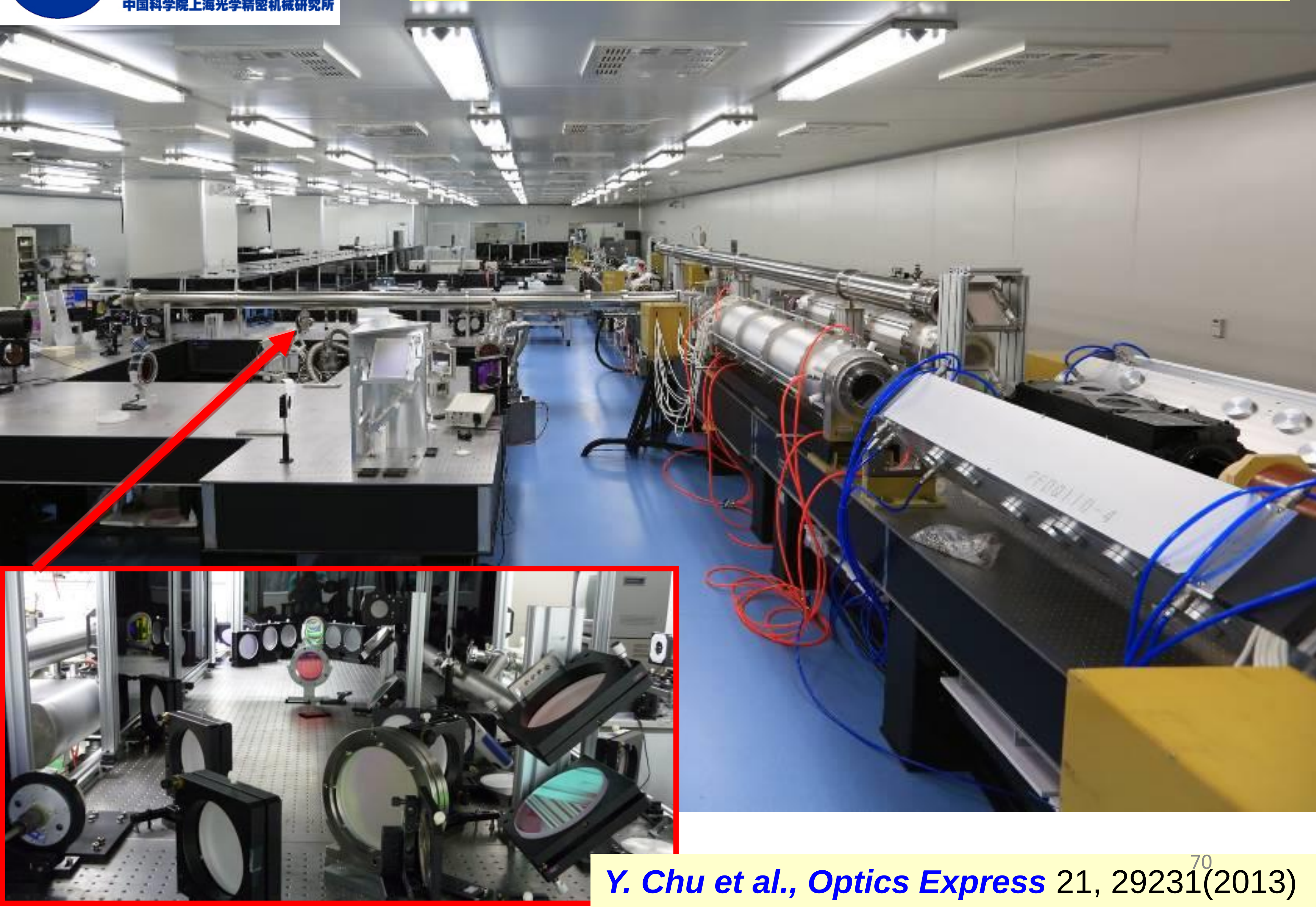




ELI-NP Facility

SIOM
中国科学院上海光学精密机械研究所

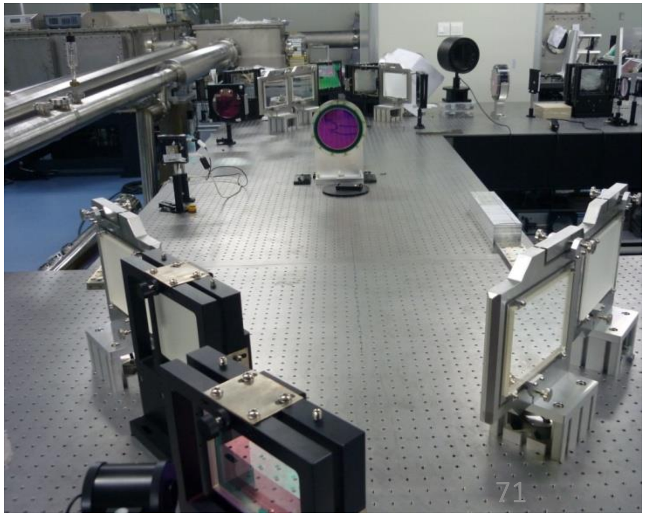
The 2PW laser facility in 2013



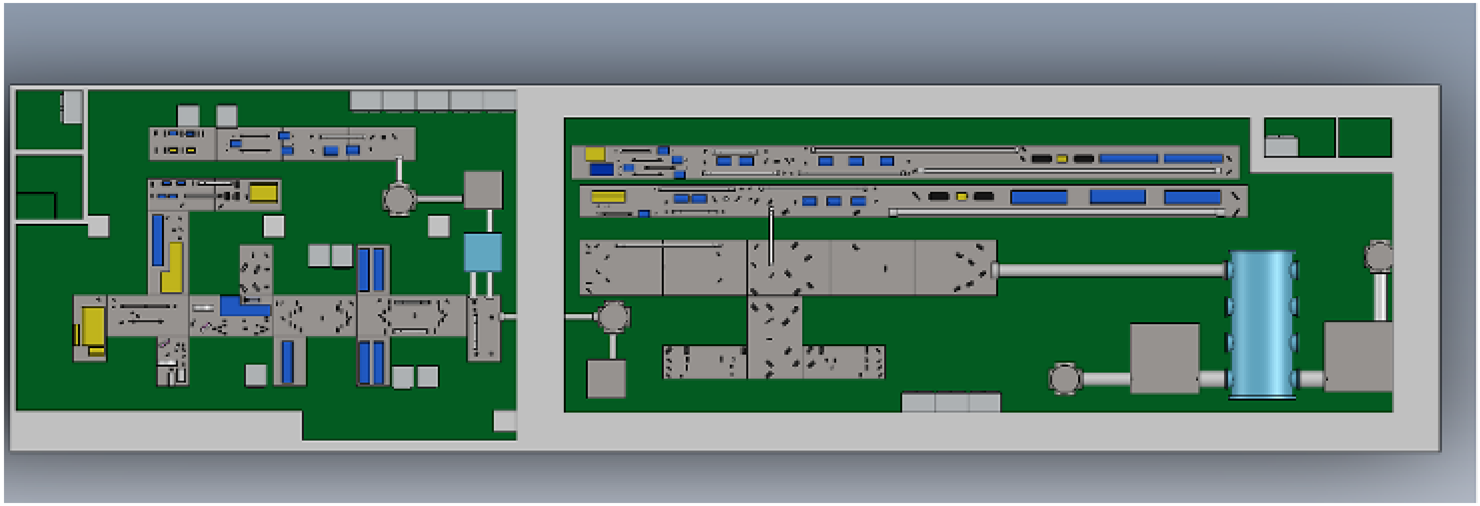
Y. Chu et al., Optics Express 21, 29231(2013)

5PW Ti:sapphire amplifier (2014)

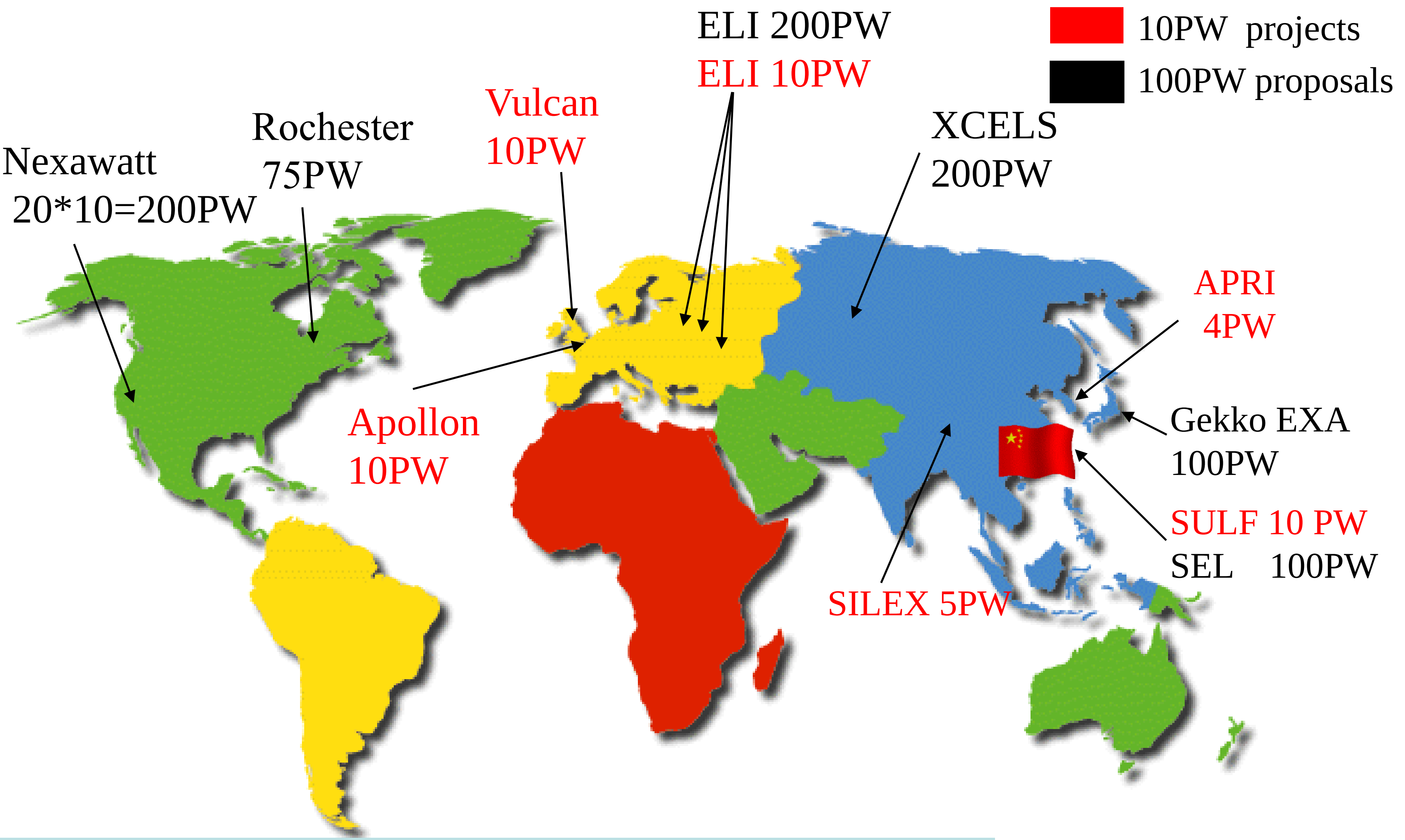
- **Four-pass Ti:Sapphire Amp.-I**
  - Ti:Sapphire: Φ80
  - E_{pump}: 60J
  - $E_{injected}$: 3.0J
  - E_{output}: 28J-35J
- **Four-pass Ti:Sapphire Amp.-II**
  - Ti:Sapphire: Φ150
  - E_{pump}: >300J
  - $E_{injected}$: 35J
  - E_{output}: 192J



The 10PW Laser Facility under construction (2015)



10PW-100PW laser projects and proposals



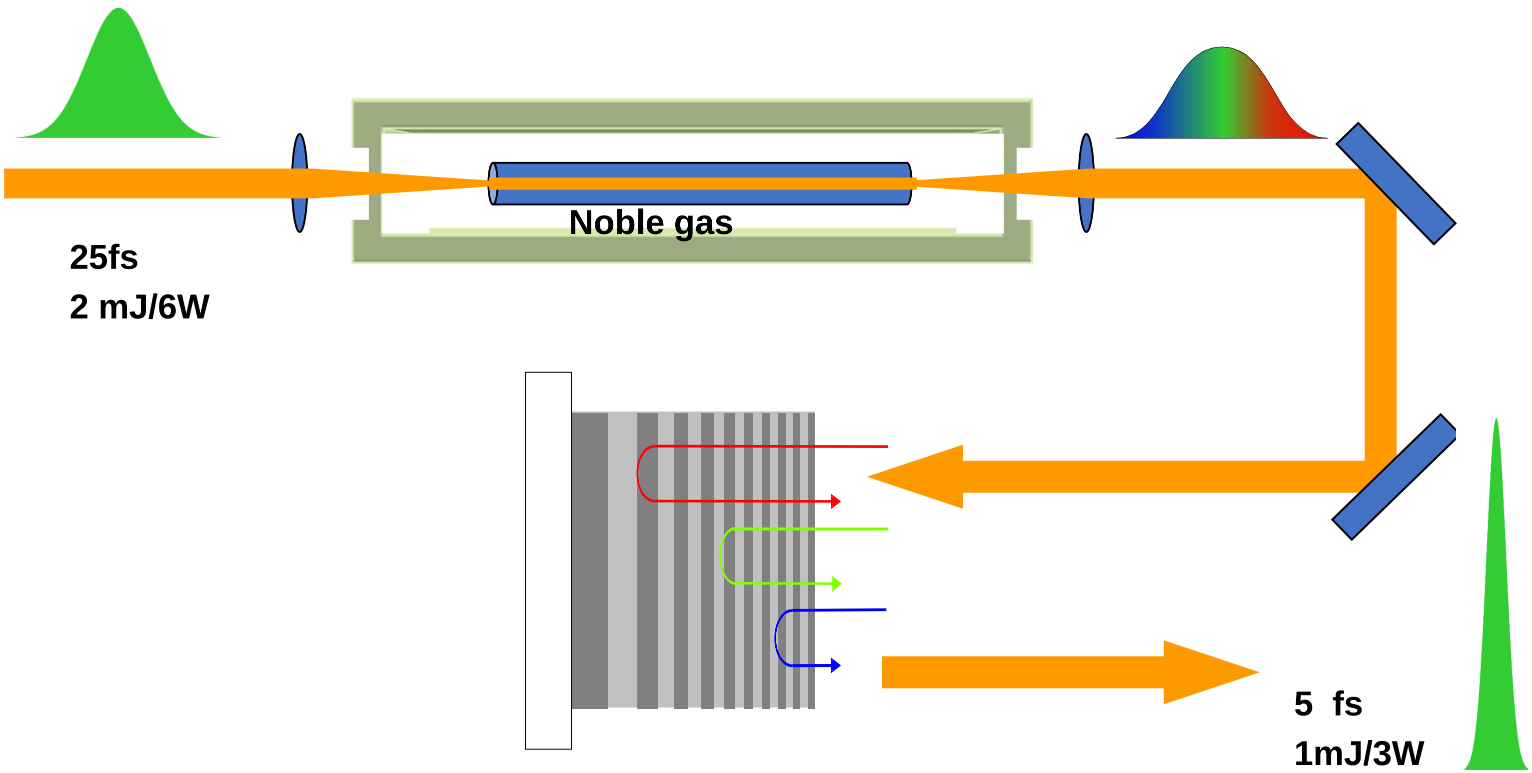
In 2016 SIOM has produced 5.3PW laser pulses

Science 355, 785 (2017)
Opt. Express 25, 5169(2017)

Outline

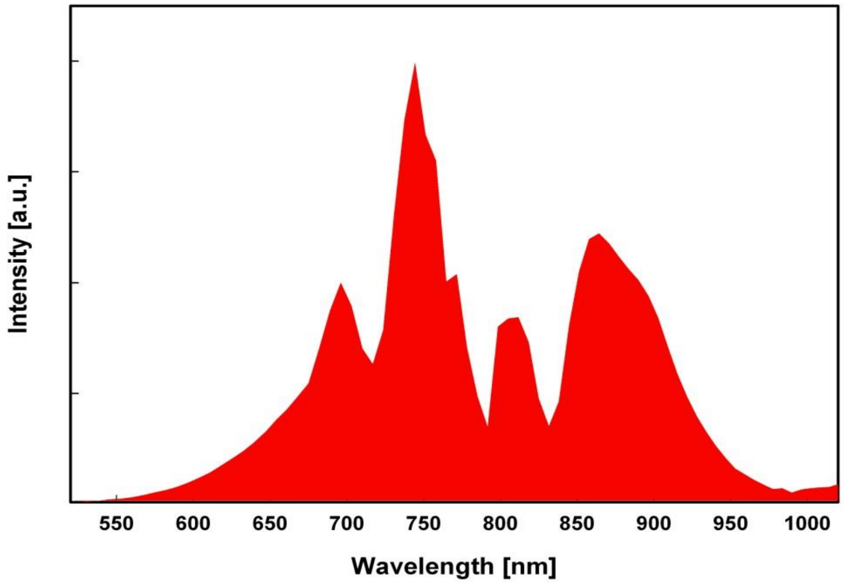
- General Introduction
- Ultrahigh Intensity Laser-Toward multi-PW power
  - Oscillator-Generation of femtosecond laser
  - Stretcher-Management of dispersion
  - Amplifier-Boost laser energy
  - Compressor-compensate dispersion for high peak power
  - Enhancement on contrast ratio
  - Typical PW laser facilities in the world
- Ultrafast Laser-Toward Few Cycles and Attosecond Pulse
- Optical Parametric Amplifier-Toward mid-infrared range
- High average power-Toward All-Solid State Amplifier
- Acknowledgement

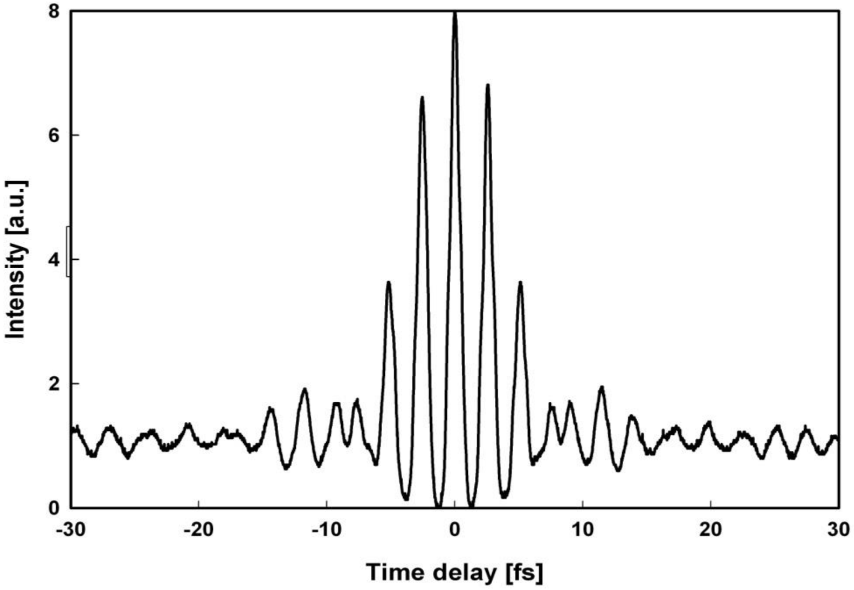
Hollow fiber spectrum broadening—Chirped mirror compressor



S. Sartania, Z. Cheng, M. Lenzner, G. Tempea, Ch. Spielmann, F. Krausz, K. Ferencz, **Opt. Lett.** 22, 1562, (1997)

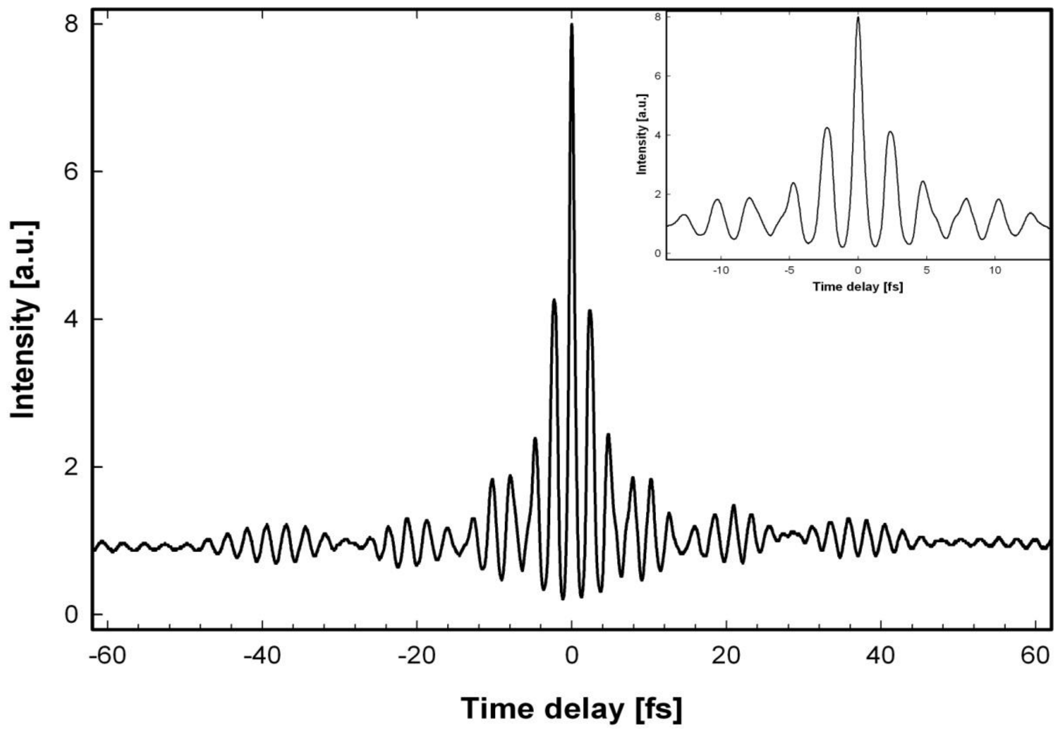
Spectrum broadening— pulse compressing





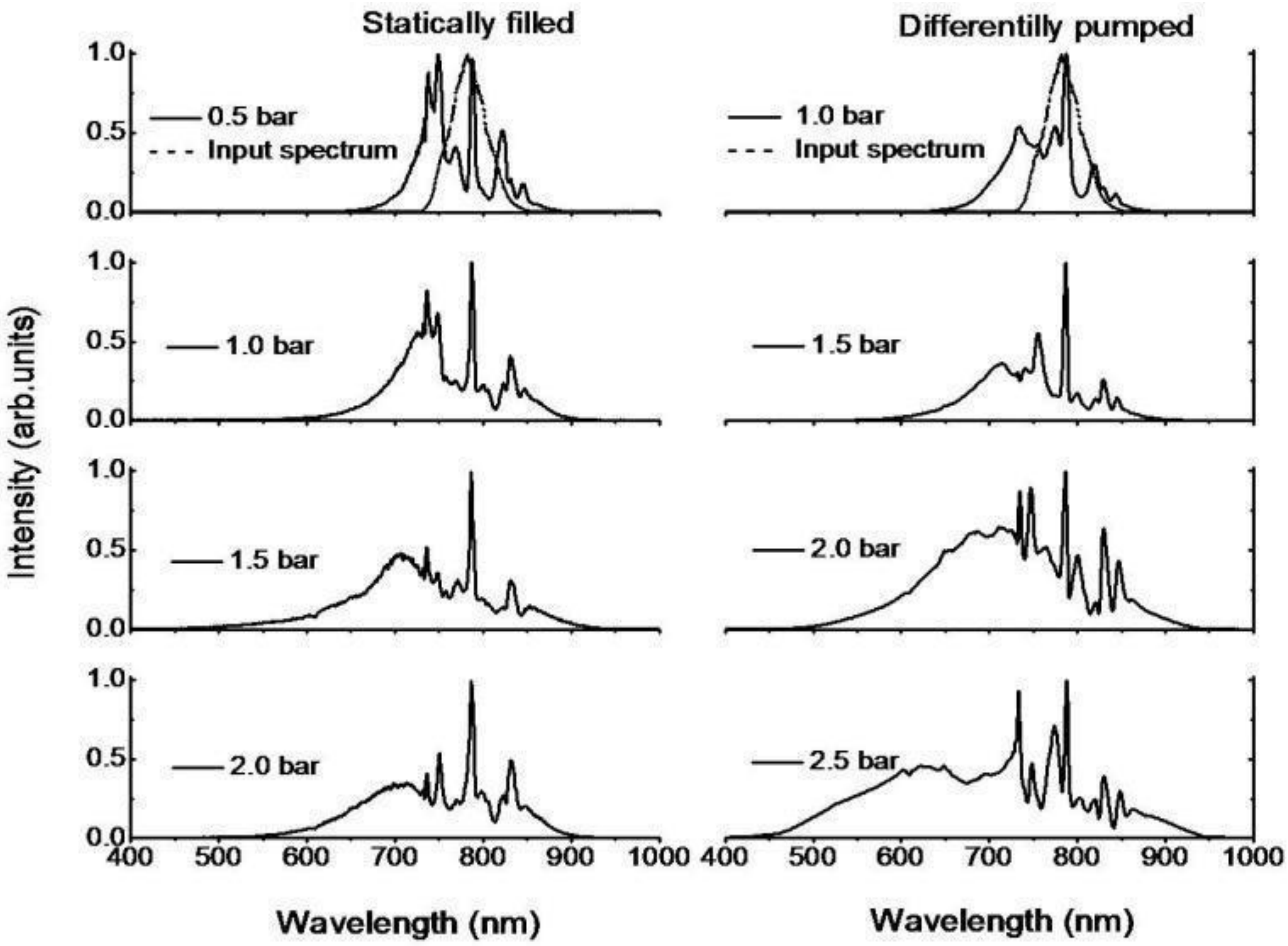
FEMTO LASERS
www.femtolasers.com

Two fringes autocorrelation



FEMTO LASERS
www.femtolasers.com

Spectral broadening in hollow fiber

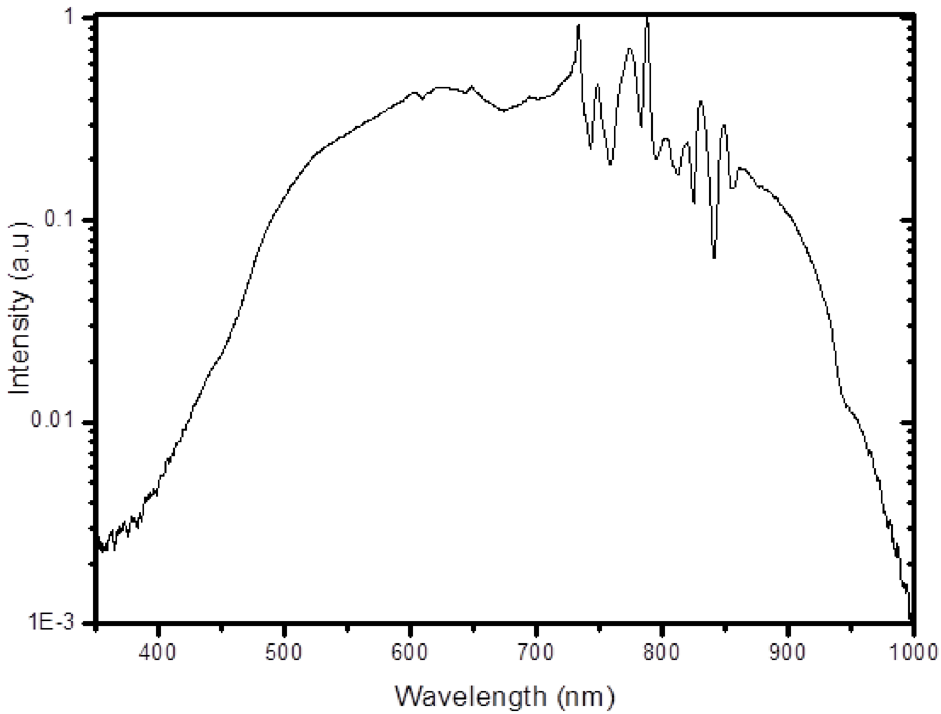


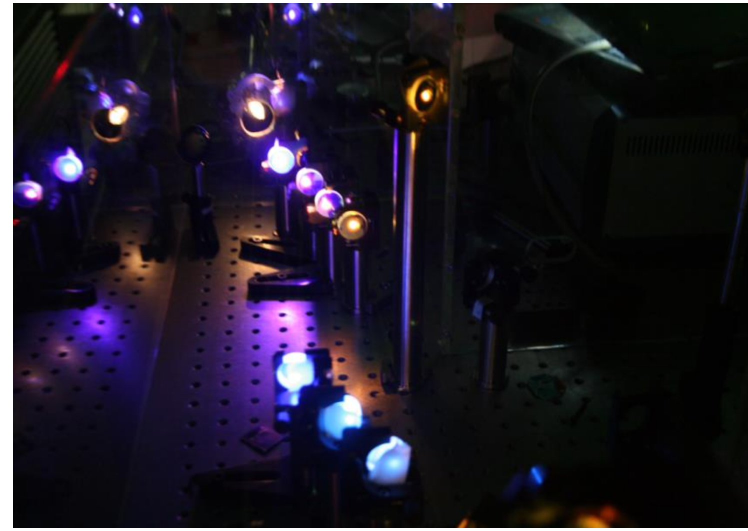
800 mW—460 mW
Transmission efficiency 57.5%

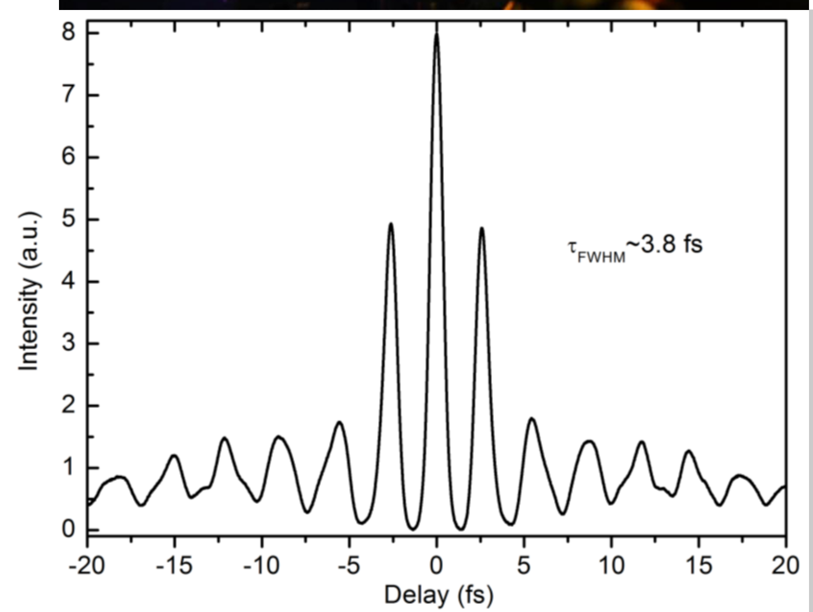
800 mW—550 mW
Transmission efficiency 68.8%

Spectrum and compressed pulse

Super continuum spectrum after hollow fiber

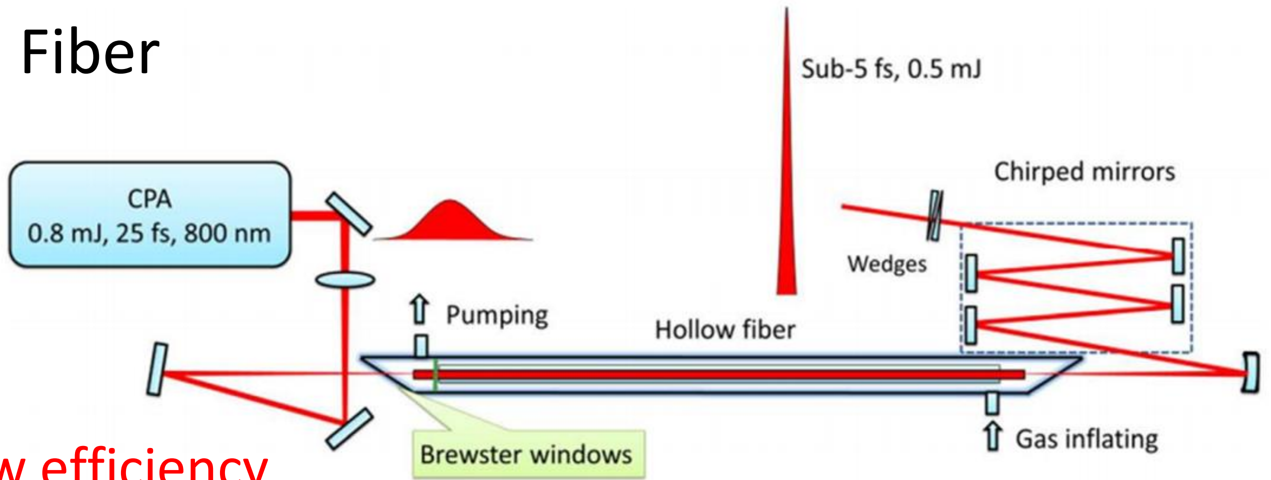






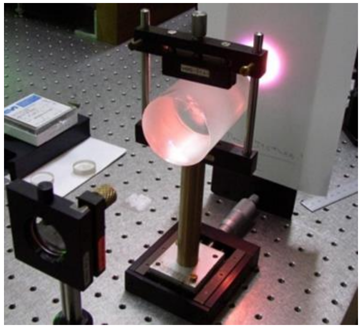
Supercontinuum Generation-Current

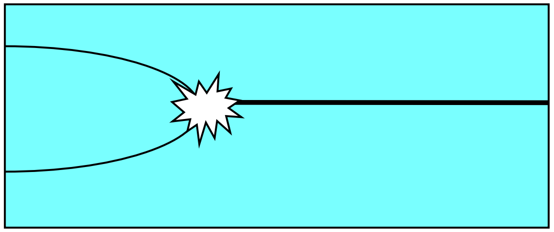
Hollow-Core Fiber



Low energy, Low efficiency
Complexity, Instability

Bulk Material





Filamentation
Material Damage

Super-continuum in Quasi-Waveguide

Nonlinear quasi-optical waveguide for ps pulses

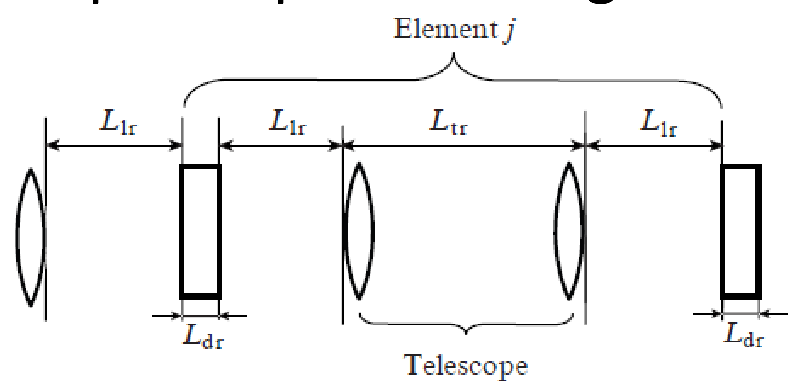
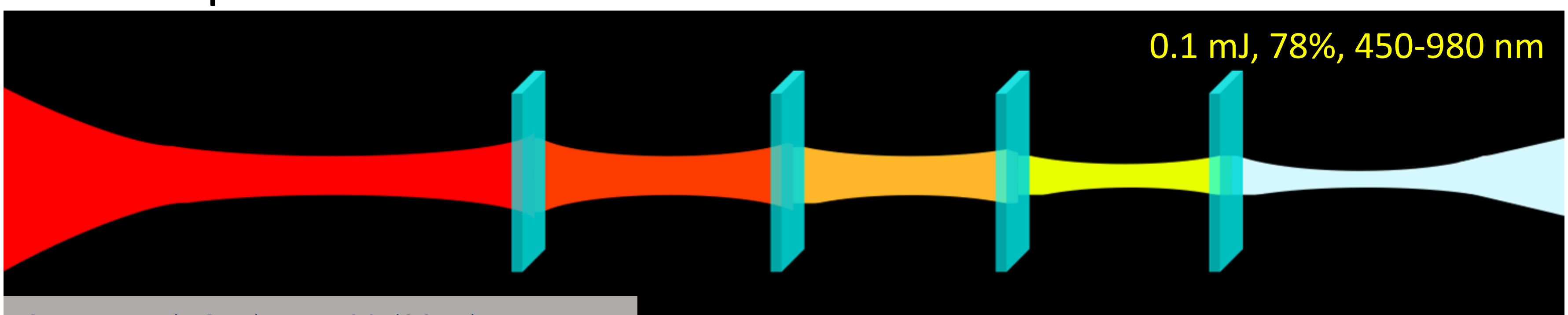


Figure 1. Fragment of a transmission line (quasi-optical waveguide) with a relay telescope.

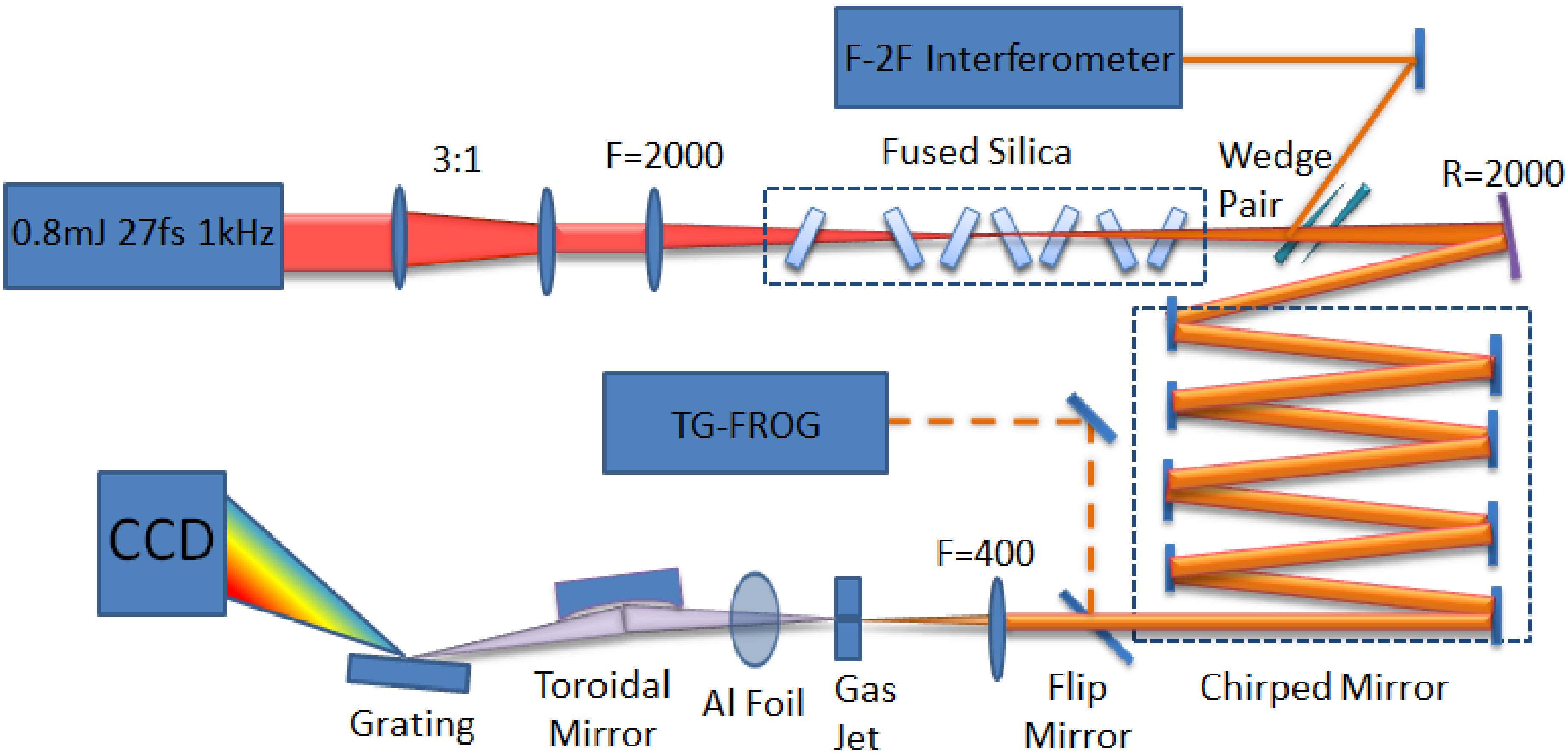
S. Vlasov, *et al.*, Quantum Electron. 42, 989 (2012)

Multiple Thin Plates

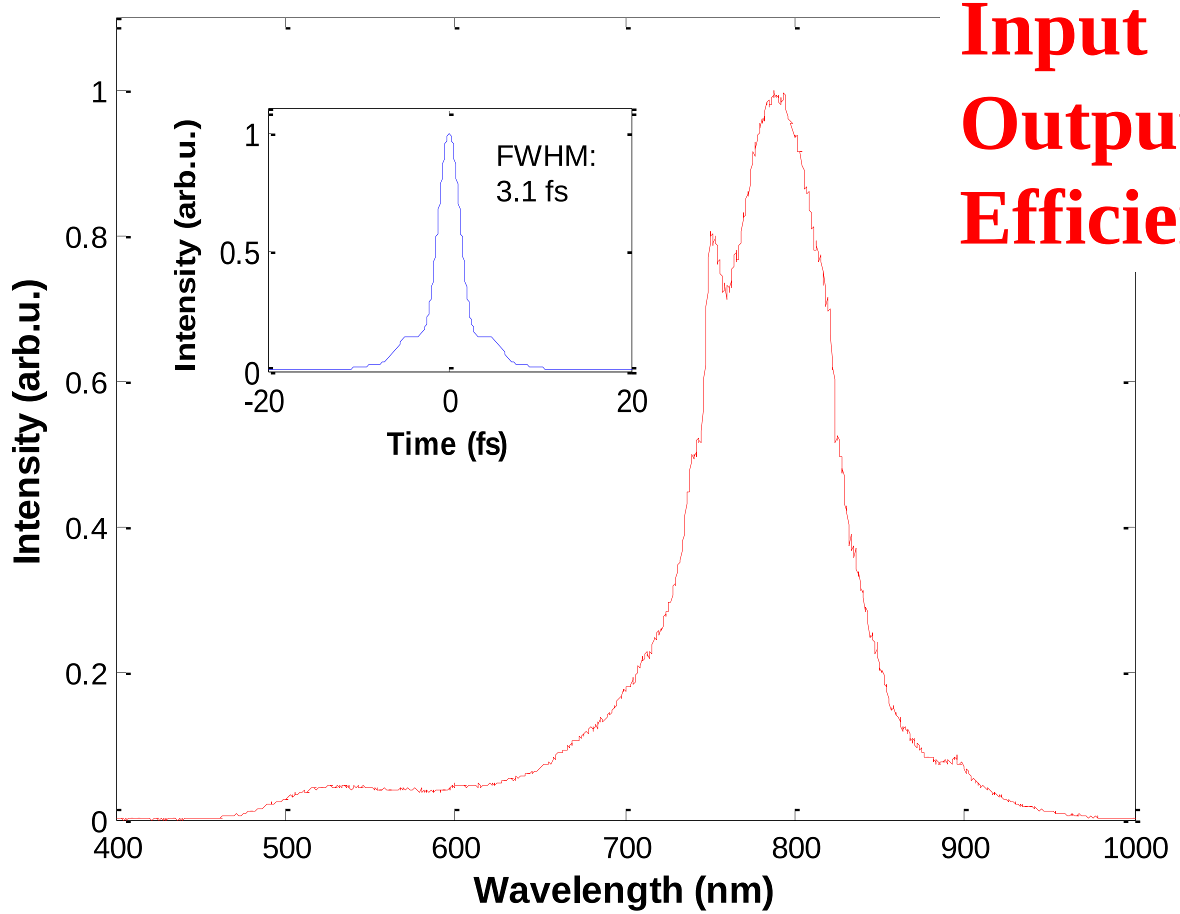


C. Lu, *et al.*, Optica 1,400 (2014)

SC in solid:Generation-Setup



Results



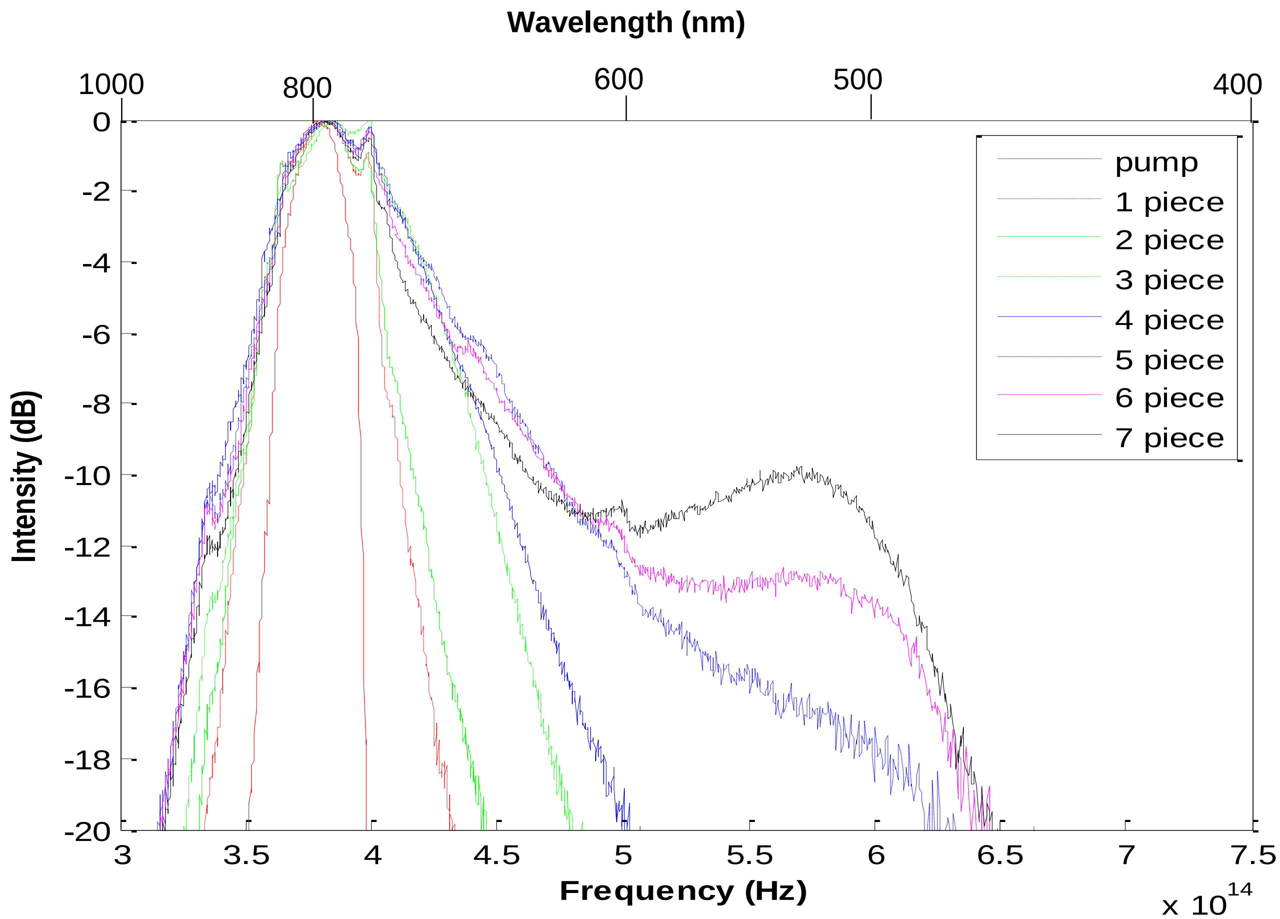
Input : 0.8mJ

Output : 0.68mJ

Efficiency: 85%

Near an octave-spanning supercontinuum (Fourier transform limit of 3.5fs)

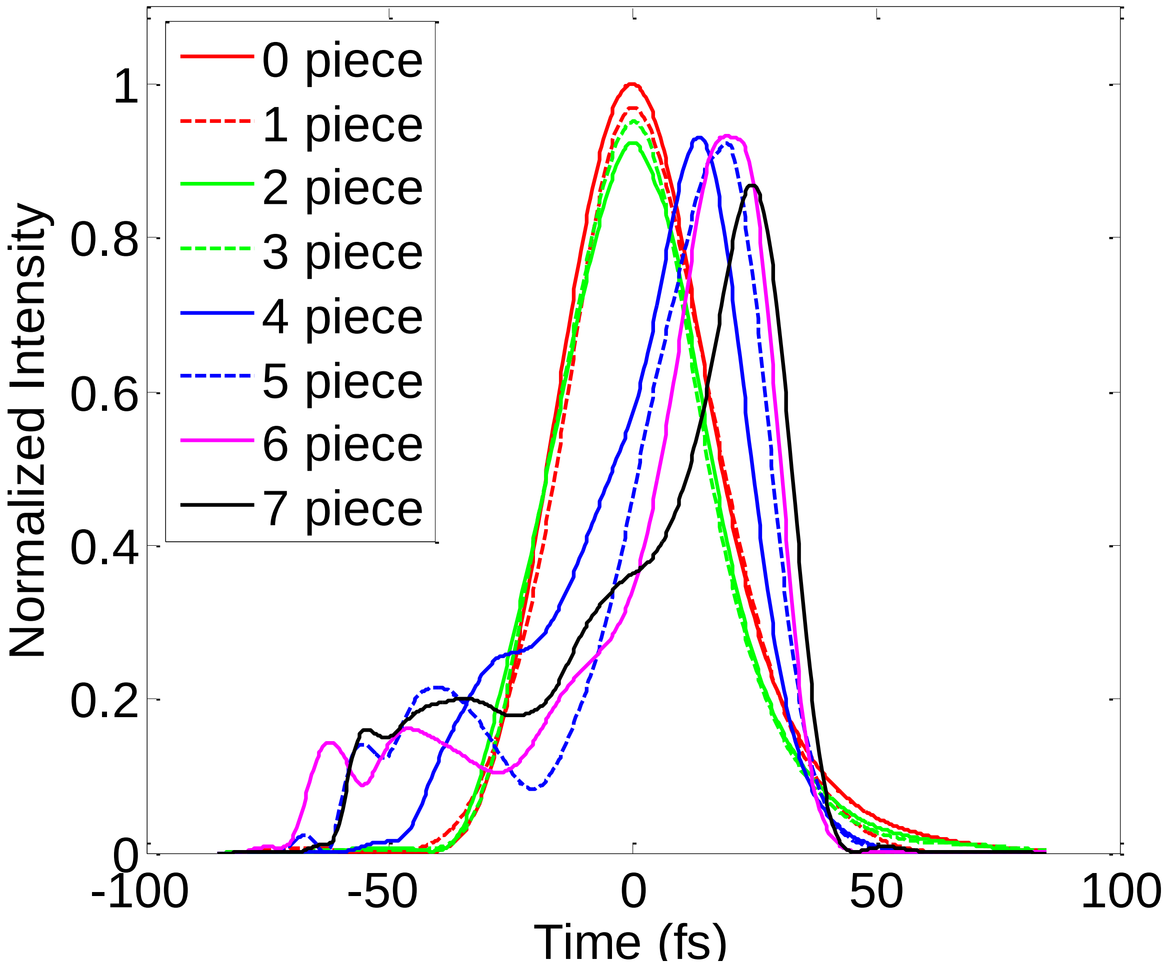
Evolution of Super-continuum



First 4 plates: symmetric broadening -- self phase modulation

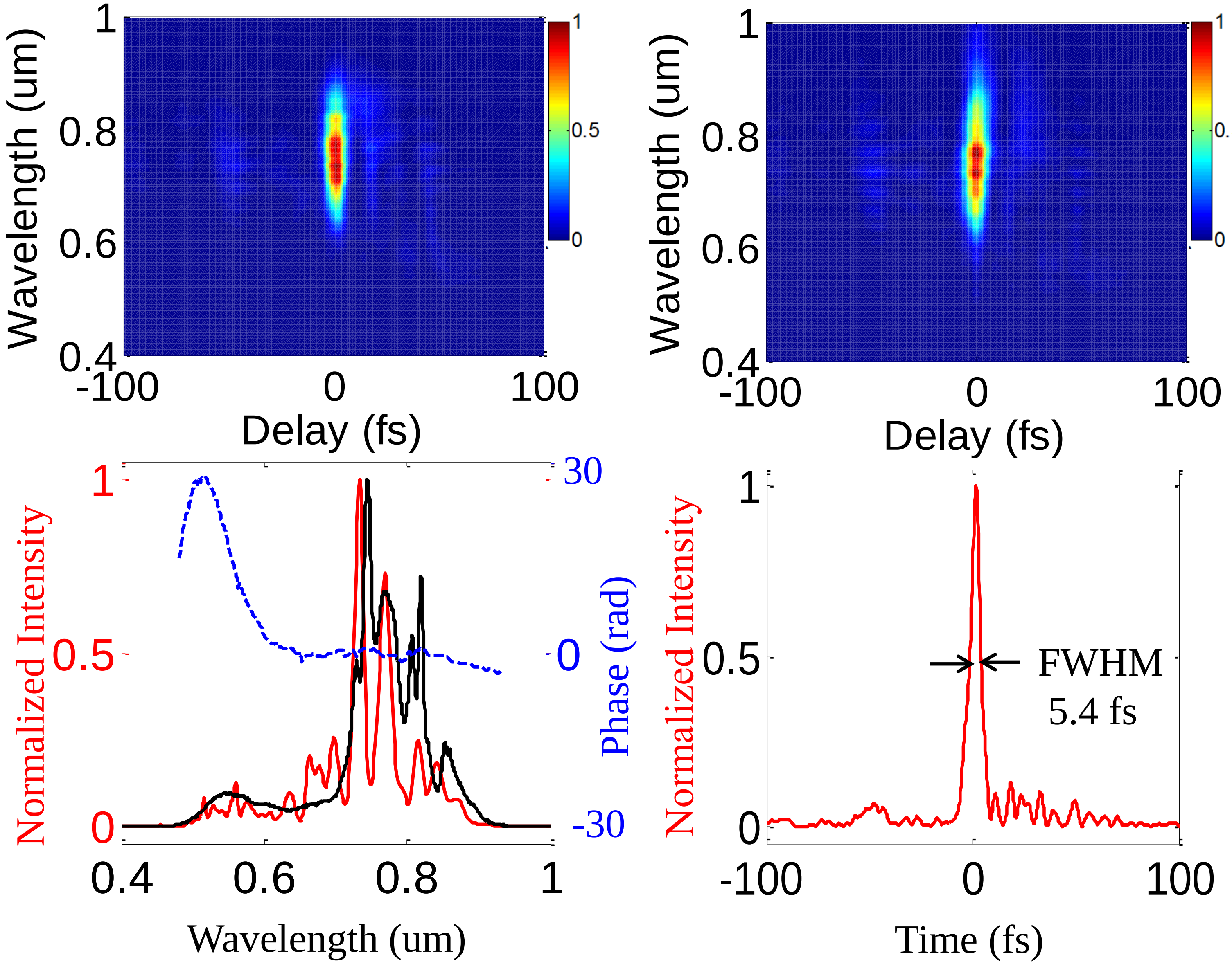
Last 3 plates: asymmetric broadening -- self steepening

Evolution of Pulse Shape

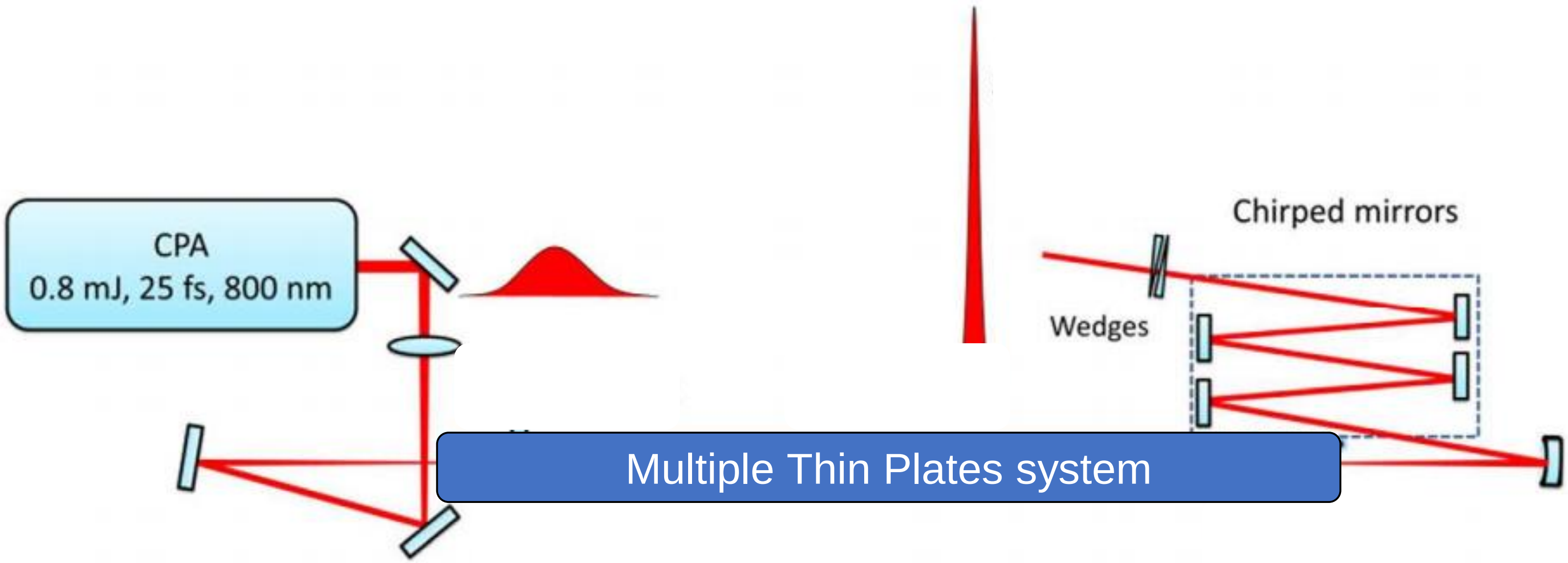


Self steepening in the last three plates

Compress to 5.4 fs by Chirp Mirrors

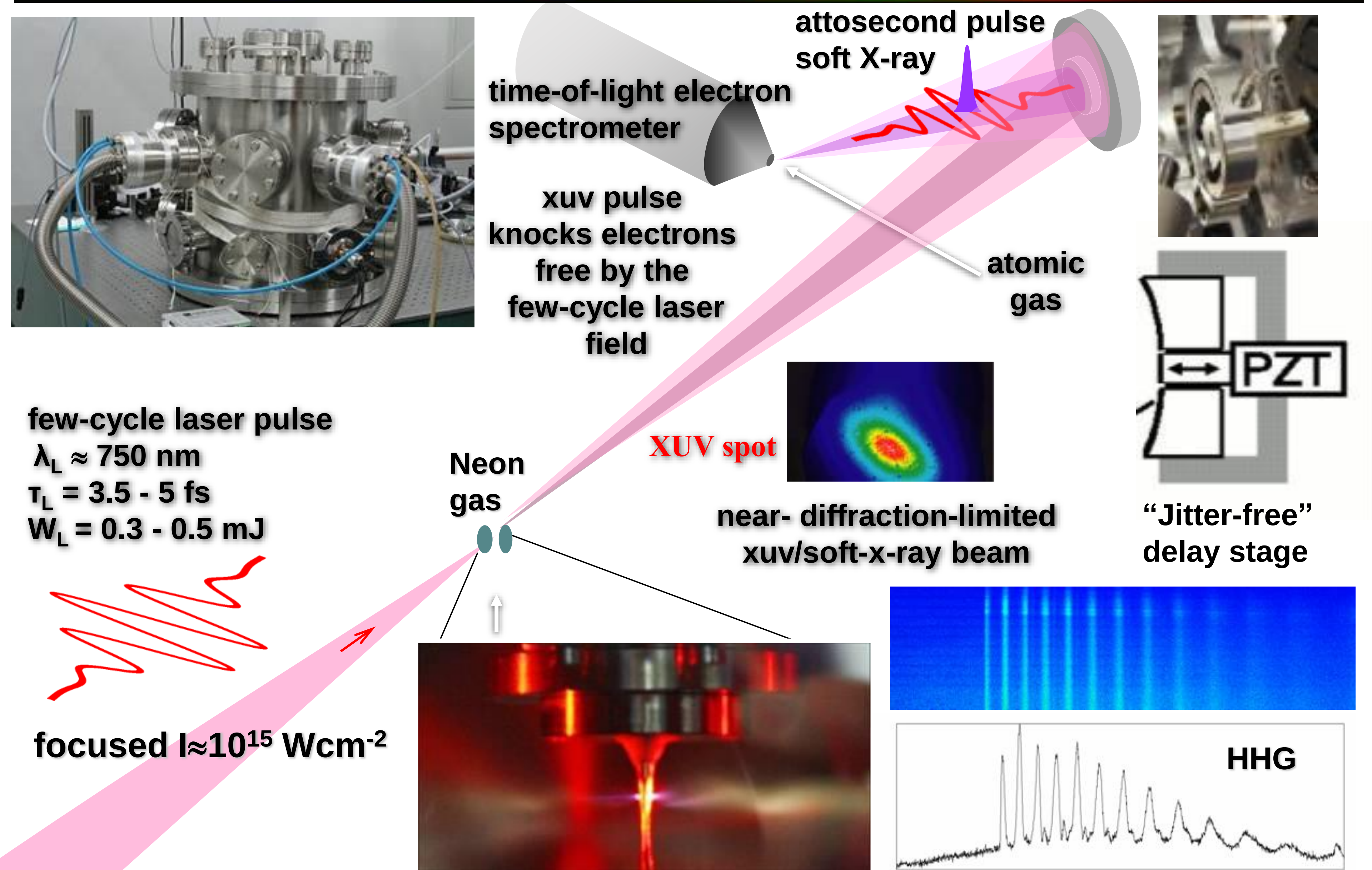


Comparison hollow fiber and Multi-plates scheme for continuum

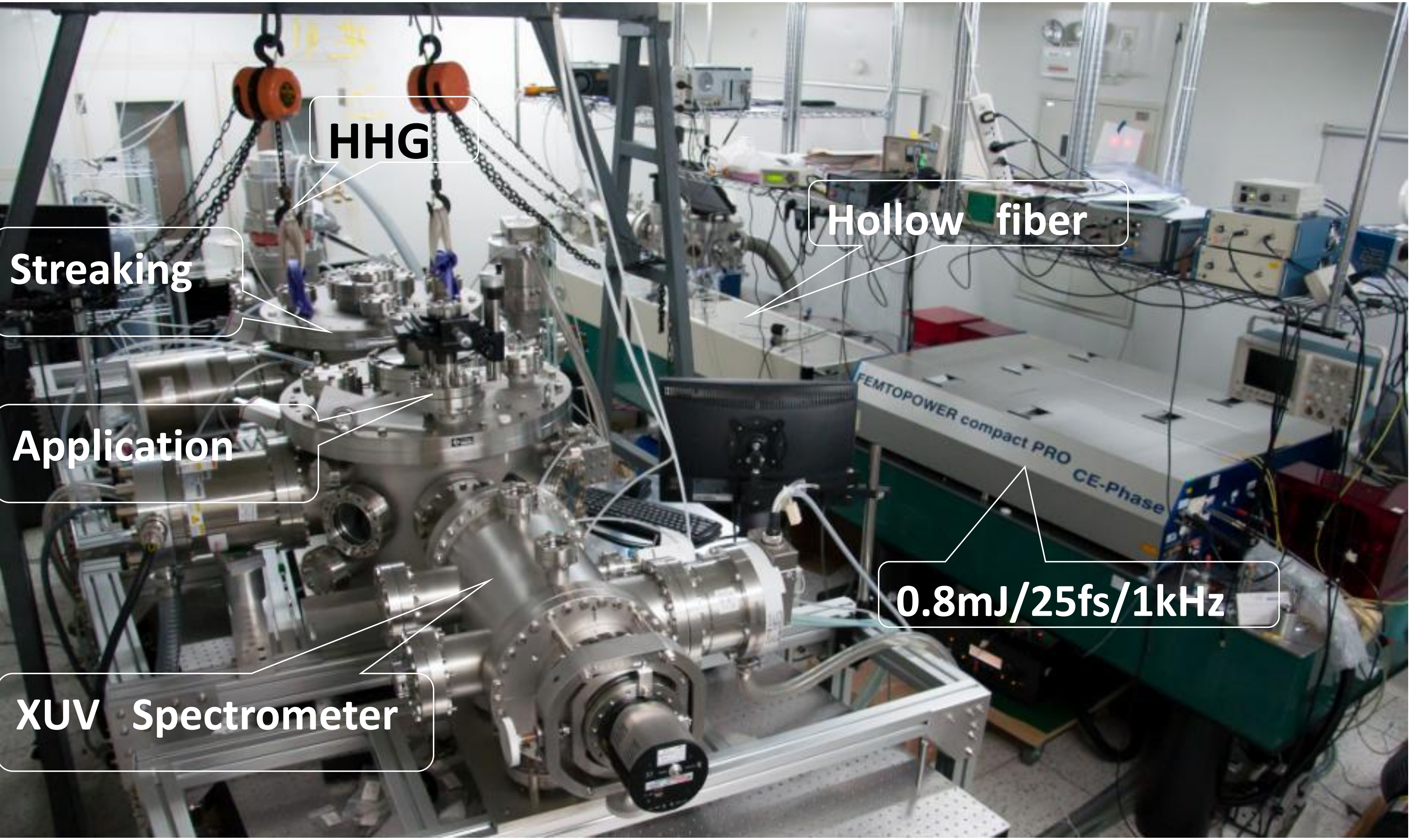


Hollow-core fiber	Fused silica plates
Core size limits the input energy	Scalable to much higher energy
Sensitive to beam pointing	Active stablization not required
Unstable	Robust
Efficiency : 50-60%	Up to 85%

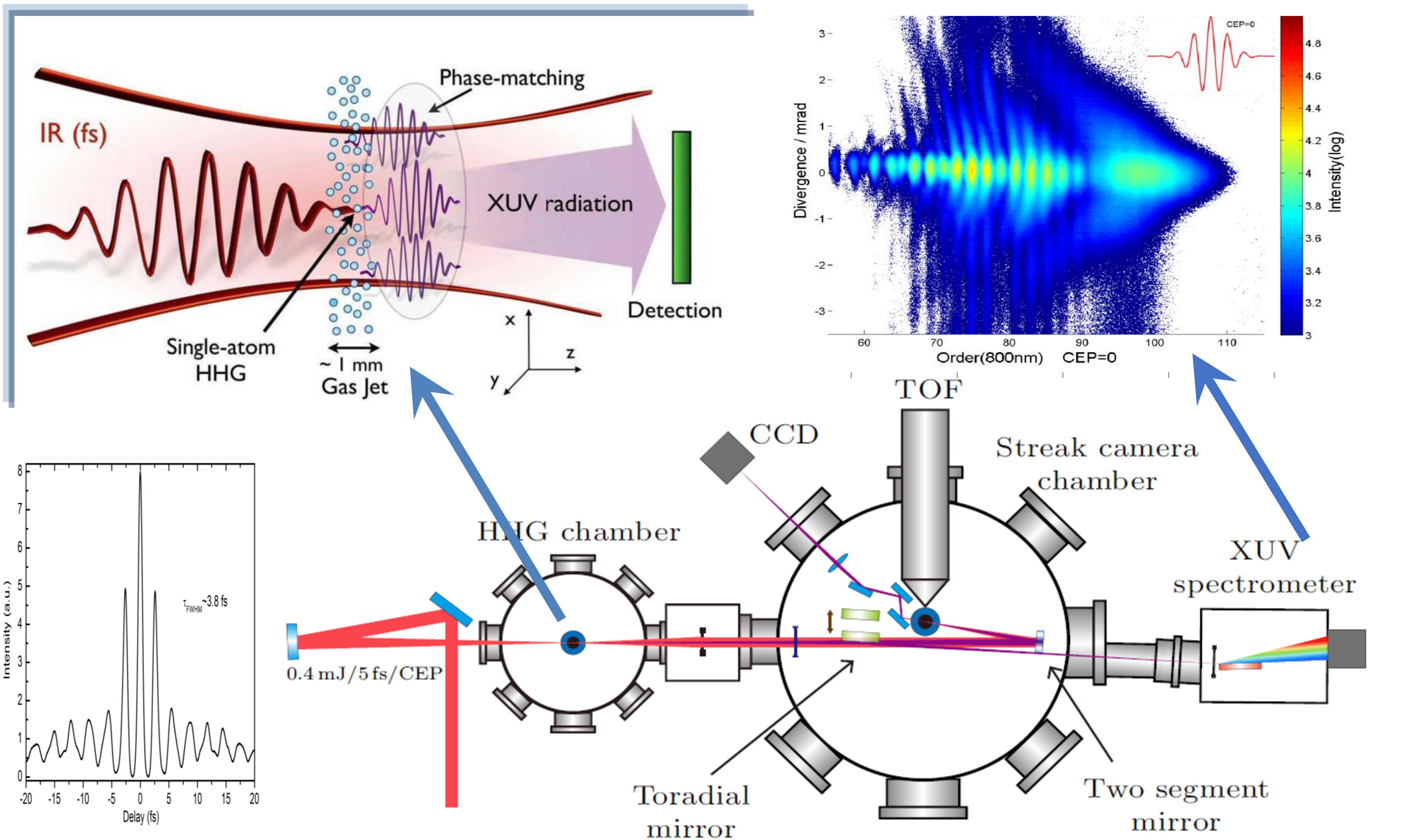
Experimental layout for HHG and attosecond pulse



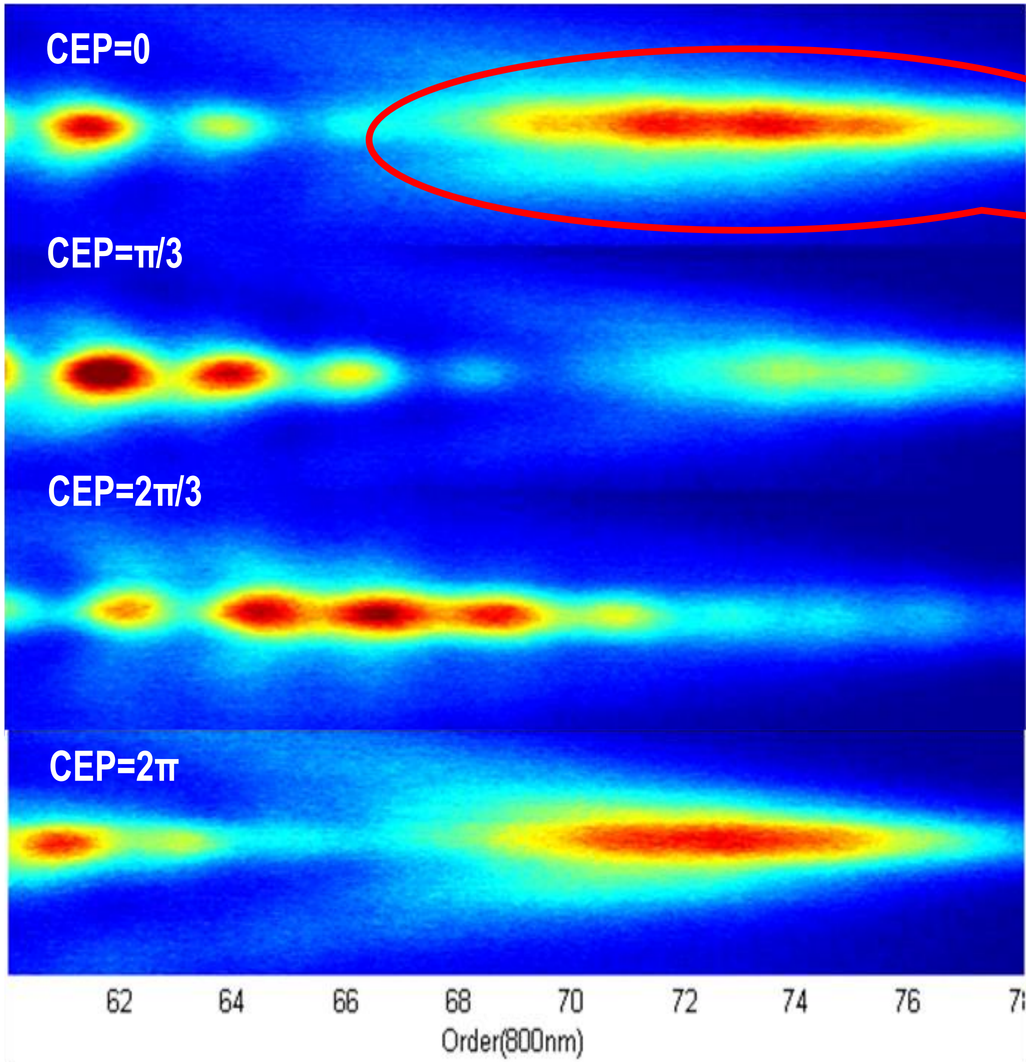
Attosecond beam facility at IoP

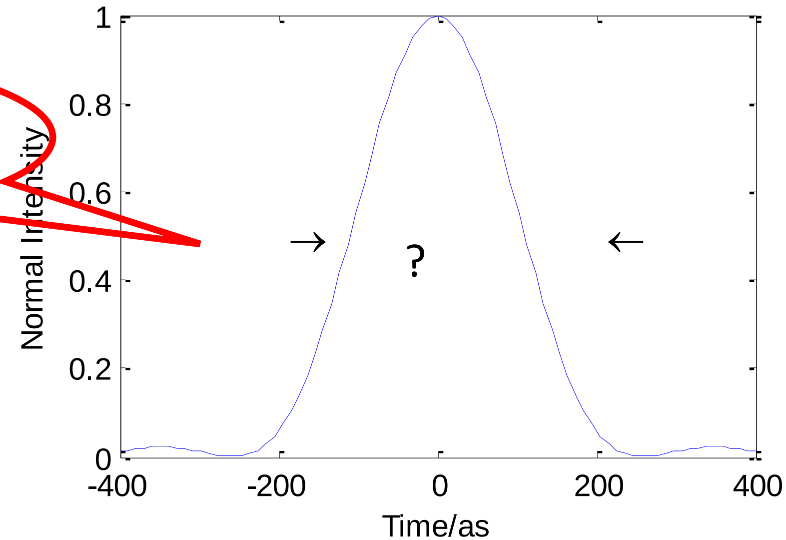


Attosecond beam facility at IoP



CEP controlled harmonic generation



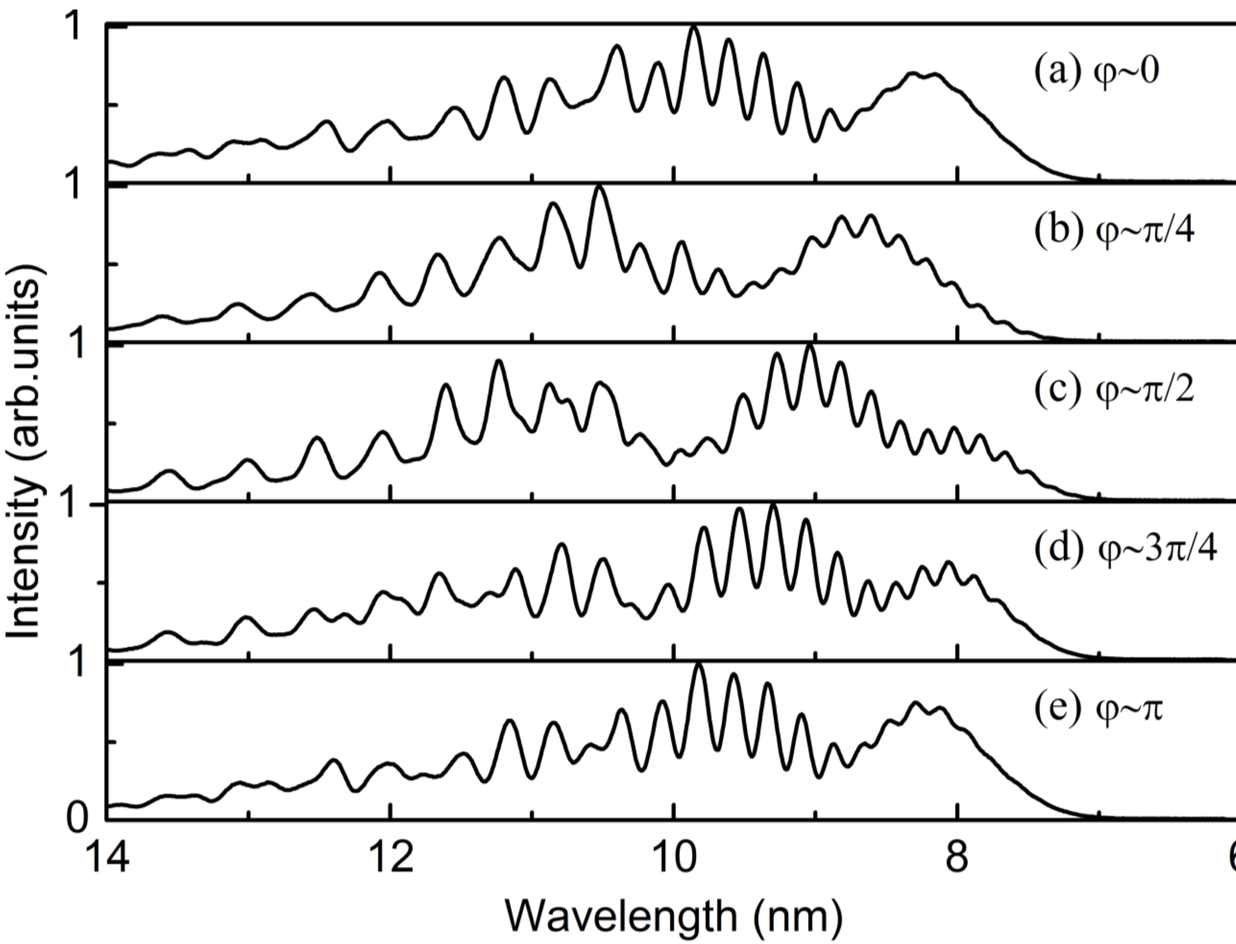


Isolated attosecond pulses

HHG with CEP:

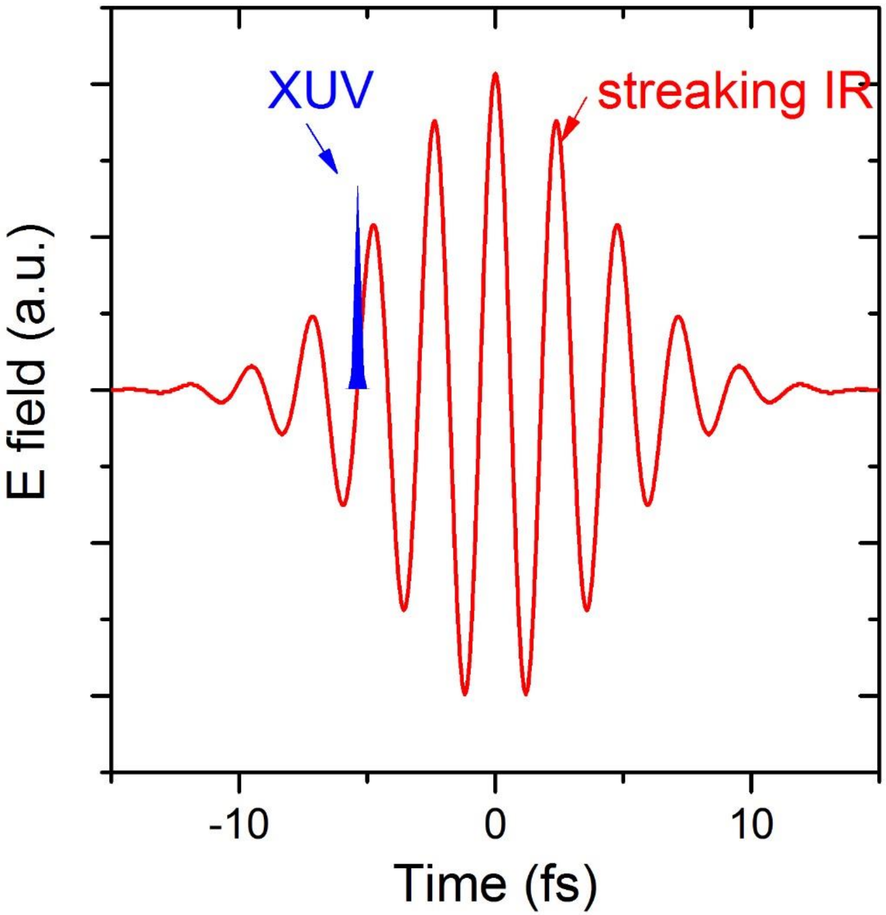
It shows the CEP can control the electrical field of attosecond light.

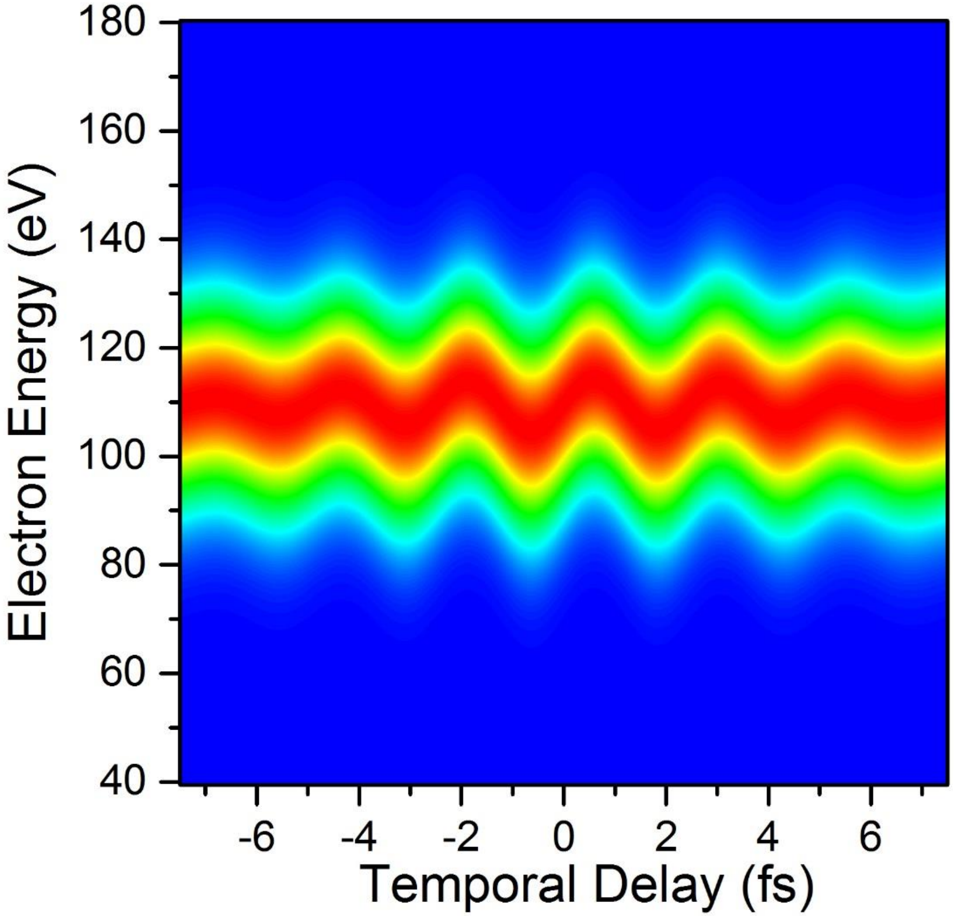
HHG spectrum driving by CEP locking with long temporal domain



HHG vs CEP, (a)~(e) show HHG spectra with CEP change from 0 to π， step is π/4.

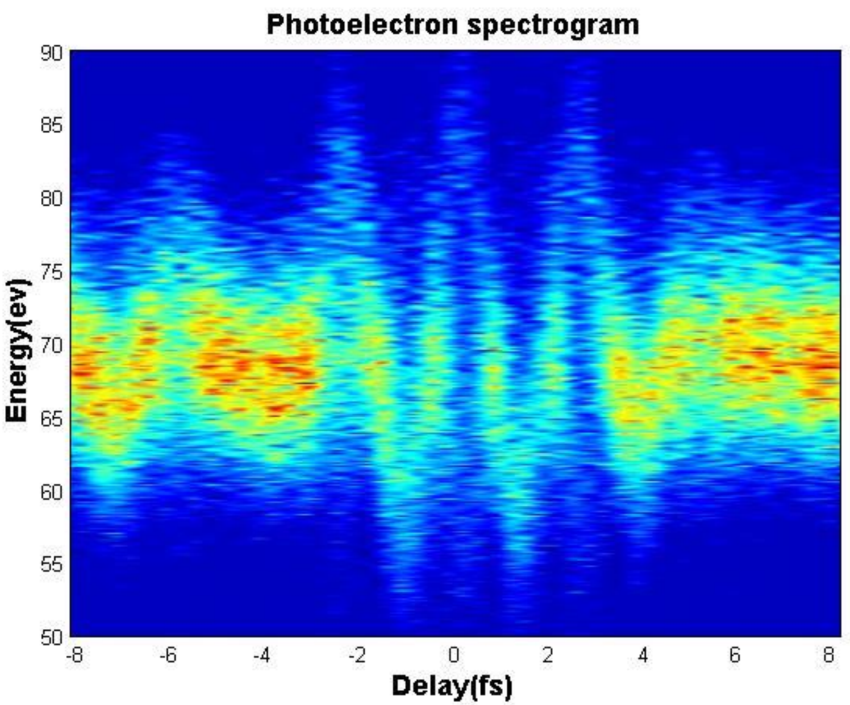
Attosecond Streaking Spectroscopy(ASS)

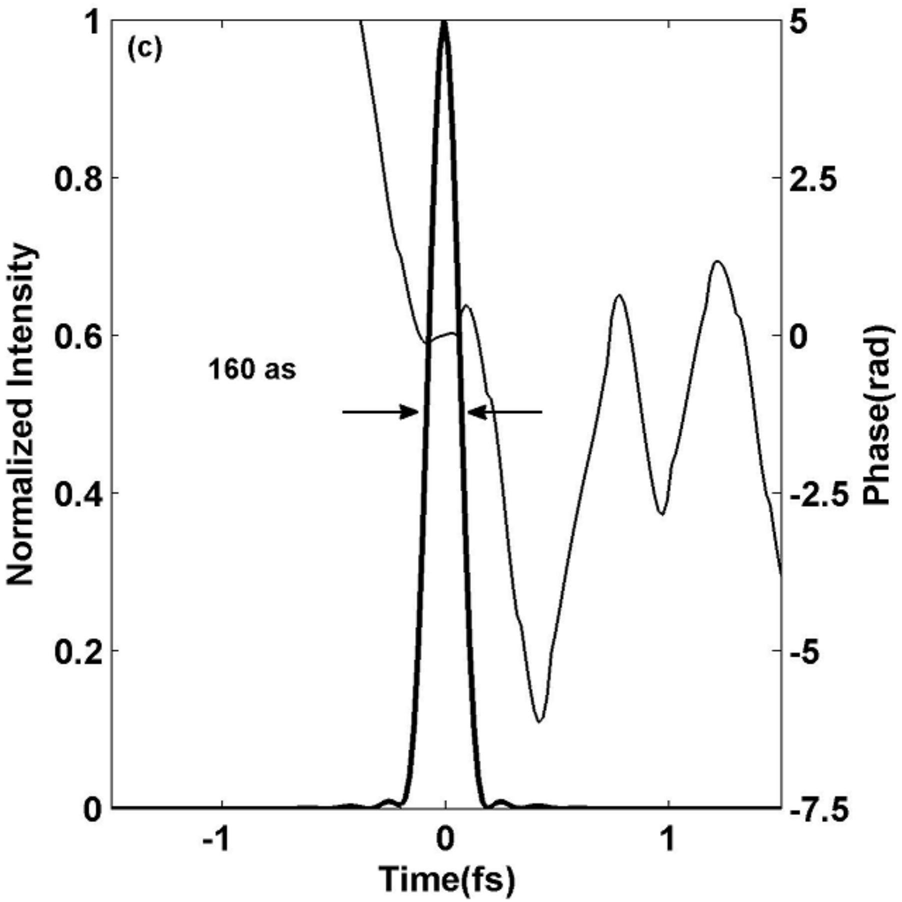




Itatani *et al.* Phys. Rev. Lett. **88**, 173903 (2002).

Generation and measurement of isolated attosecond pulse





Chin. Phys. Lett. 30, 093201(2013)
Opt. Express 21(15), pp 17498(2013)

We successful measured the streak fringe of photoelectron spectrogram for characterizing the attosecond pulse. This is first time to get attosecond laser in China.

Trend in future

- Ultrahigh intensity femtosecond laser driver+GDOG — High Flux

  Z. Chang et al, 200TW/5fs, PW in future, ELI

- UV femtosecond laser driver — Higher efficiency HHG, high flux,

  Ming Chang Chen, Tsing-Hua University

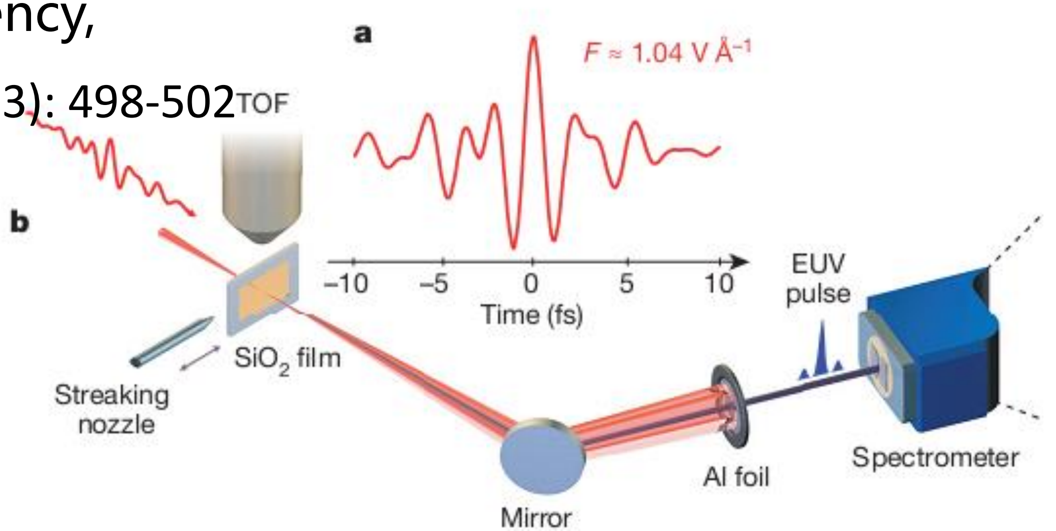
- MID femtosecond laser driver — High cutoff eV, short pulse
  T.Popmintchev et al, Science 336, 1287(2012)

- Dual wavelength laser driver — High efficiency.

  E. J. Takahashi *et al.*, PRL. **104**, 233901 (2010), Nat Commun. **4**:2691 (2013)

- Solid state HHG — High efficiency,

  Luu T T et al. *Nature*, 2015, **521**(7553): 498-502



Toward emerging science:

Attosecond high field physics

In future:

Higher Flux

Shorter Pulse

Shorter Wavelength

HHG and attosecond pulse driven by long wavelength laser

HHG cutoff photon energy

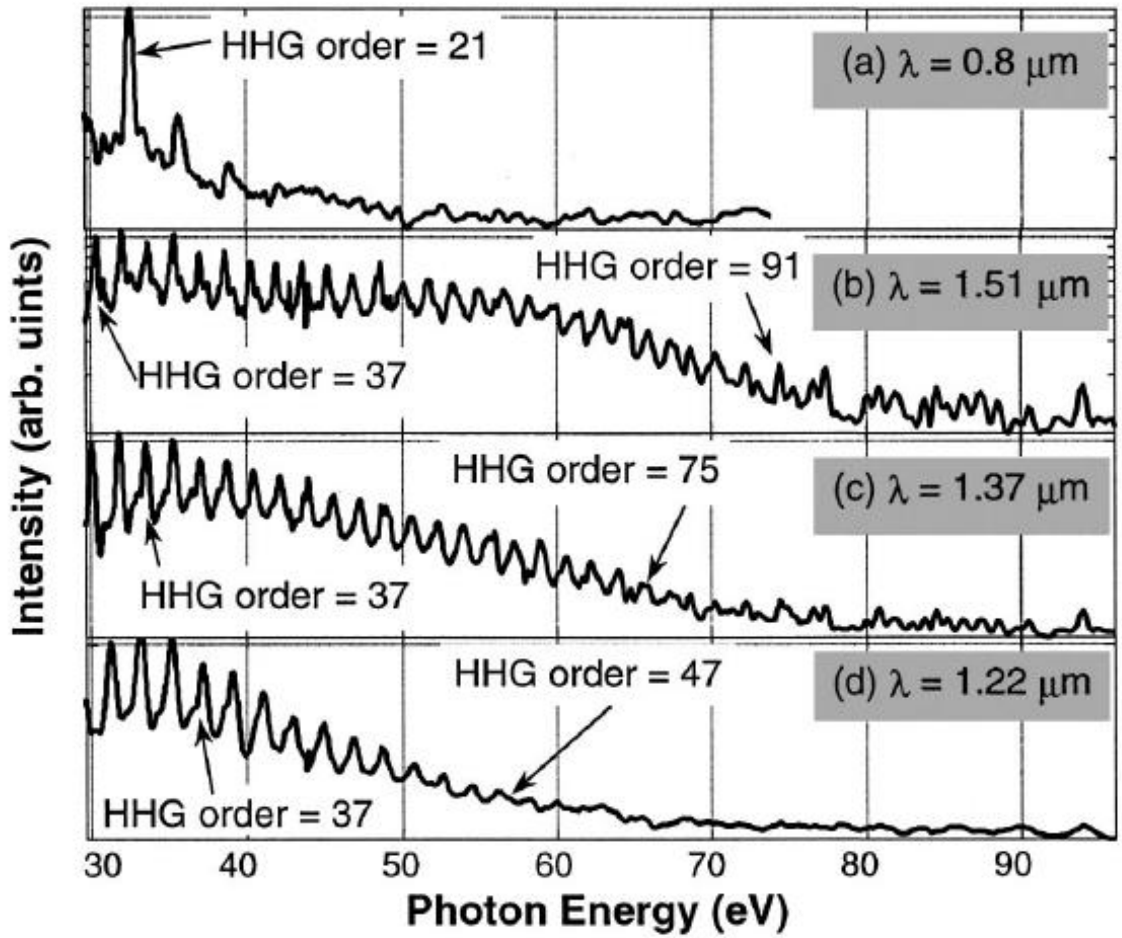
$$E_{cutoff} = I_p + 3.17U_p$$

$$U_p \propto \ I_L \lambda_L^2$$

Increase wavelength:

$$\lambda = 0.8\ \mu m \rightarrow 1.7\ \mu m$$

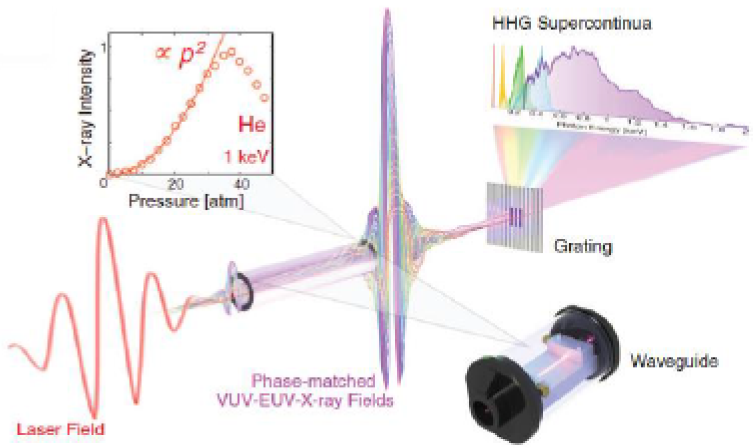
E_{cutoff} 500 eV
for
$\lambda = 1.7\ \mu m$
$I_L = 5 \times 10^{14}\ W/cm^2$



Shan & Chang, Phys. Rev. A 65, 011804(R) (2001).

keV X-ray from mid-IR, fs pulses

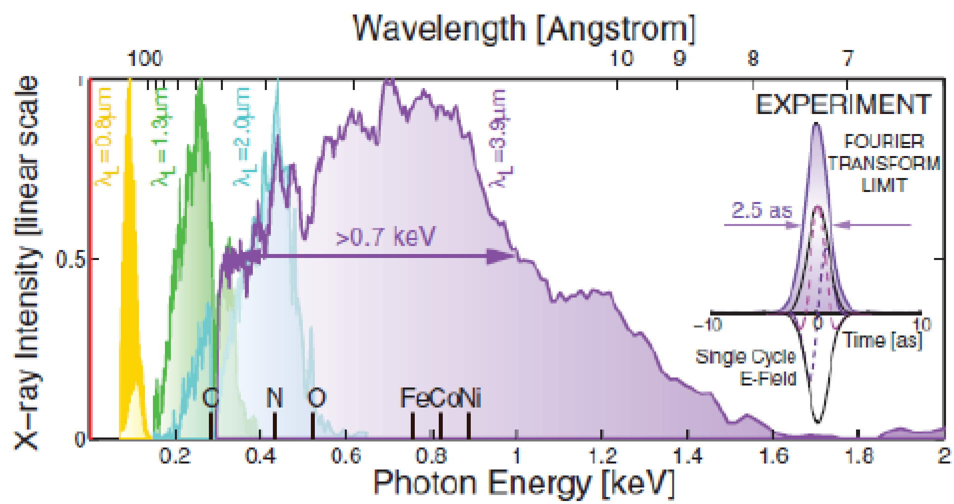
- Phase-matched emission: mid-IR (3.9 μm) pulse focused into a high-pressure gas-filled waveguide



Right combination of laser wavelength, gas pressure-length product, laser intensity

1) HHG from non-isolated emitters: electron wave-function: ~500 Å
   He atom separation: ~15 Å at 10 atm
2) Laser beam self-confinement

driving pulses: 3.9 μm, 80 fs (six cycles), 10 mJ, 20 Hz from OPCPA



T. Popmintchev *et al.*, Science **336**, 1287 (2012)

Outline

- General Introduction
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  - Oscillator-Generation of femtosecond laser
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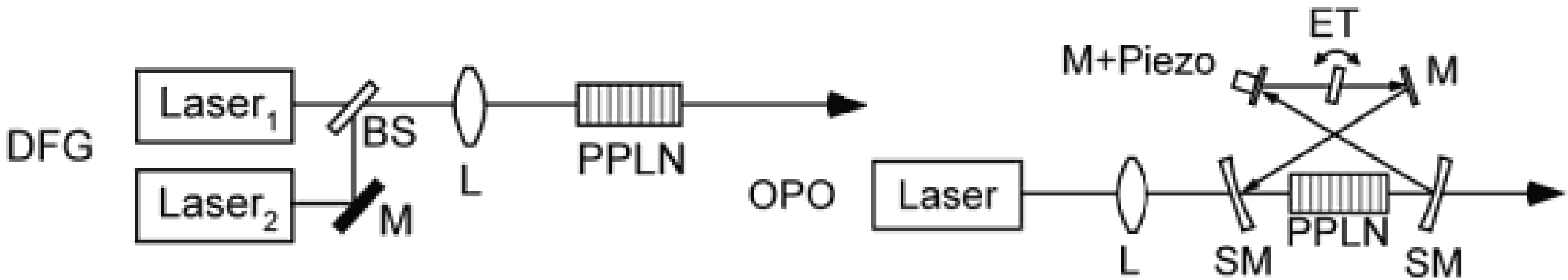
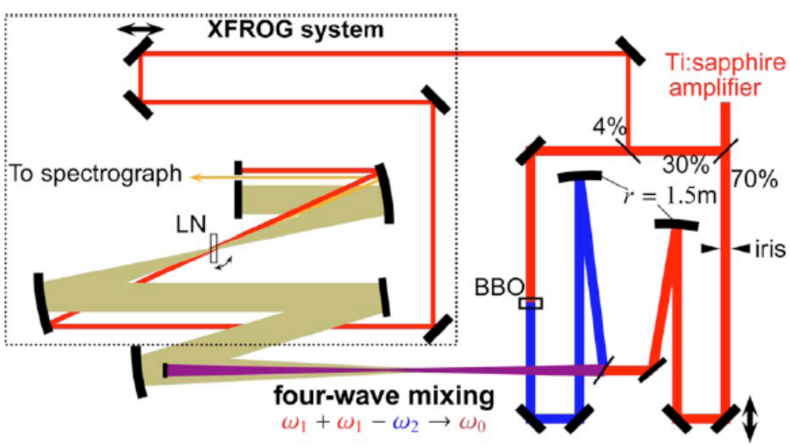
  - Amplifier-Boost laser energy
  - Compressor-compensate dispersion for high peak power
  - Enhancement on contrast ratio
  - Typical PW laser facilities in the world
- Ultrafast Laser-Toward Few Cycles and Attosecond Pulse
- Optical Parametric Amplifier-Toward mid-infrared range
- High average power-Toward All-Solid State Amplifier
- Acknowledgement

Comparison for MIR generation scheme

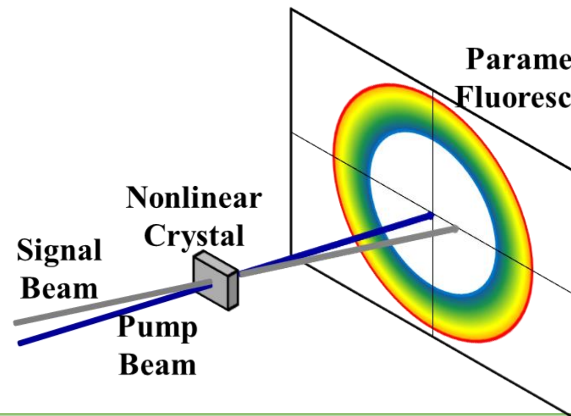


Difference Frequency Generation(DFG)
Complicated synchronization system

Optical Parametric Oscillation(OPO)
Limited by Group Velocity Mismatch

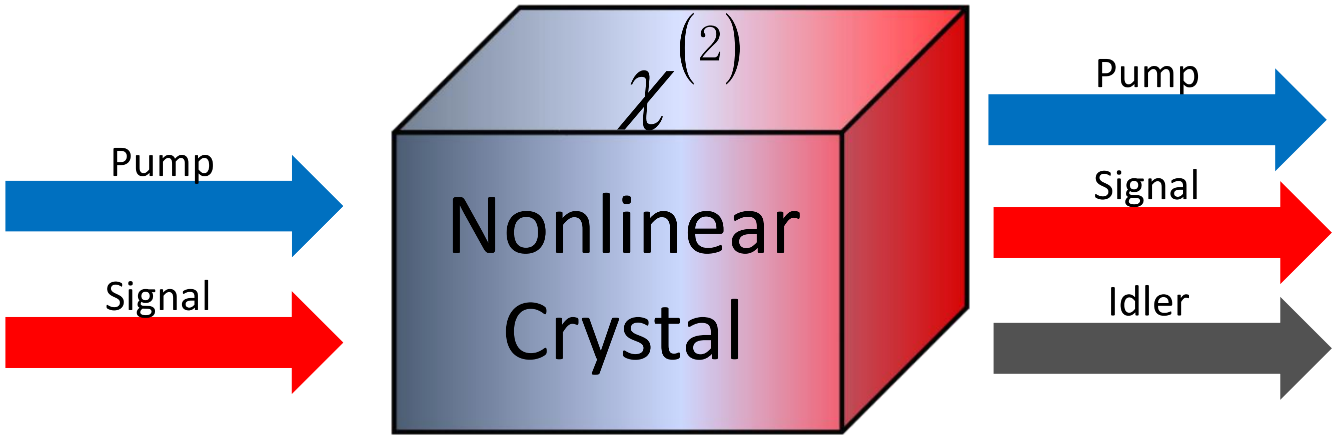


Four Wave-Mixing (FWM)
Low energy and efficiency



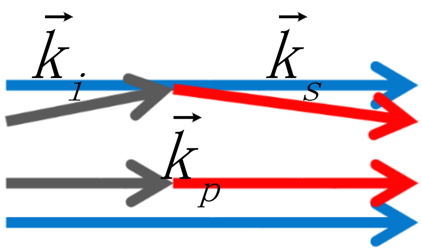
Optical Parametric Amplification(OPA)
High single pass gain $\sim 10^6$
Broad bandwidth NOPA/DOPA

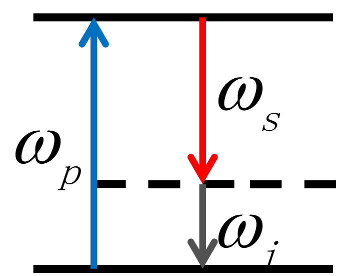
Principle of Optical Parametric Amplification



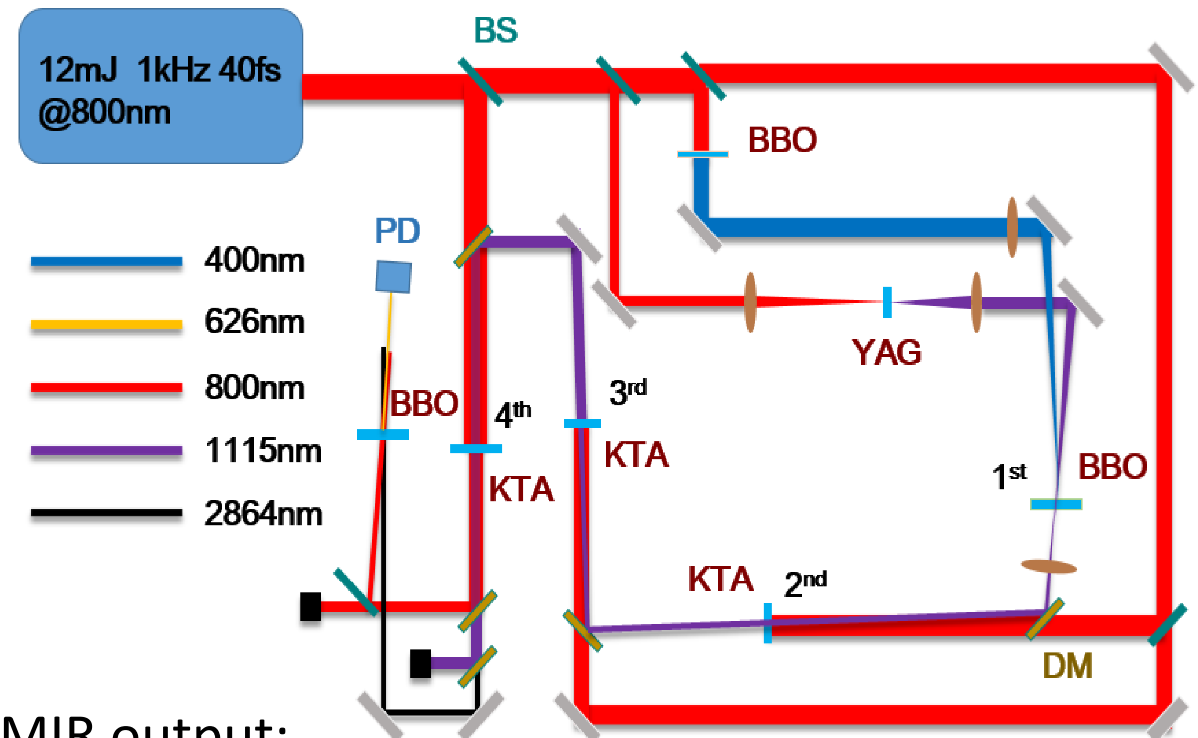
$$\hbar\vec{k}_p = \hbar\vec{k}_s + \hbar\vec{k}_i$$

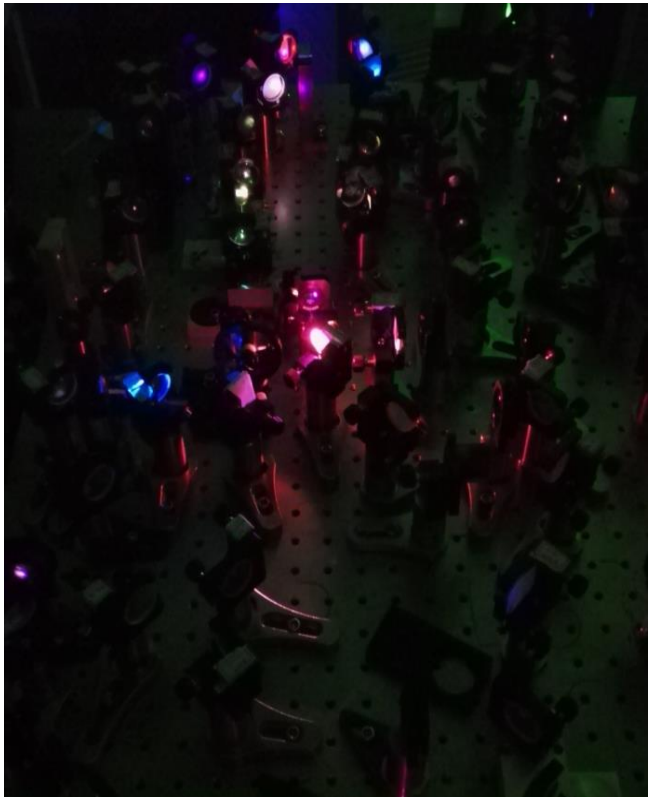
$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$





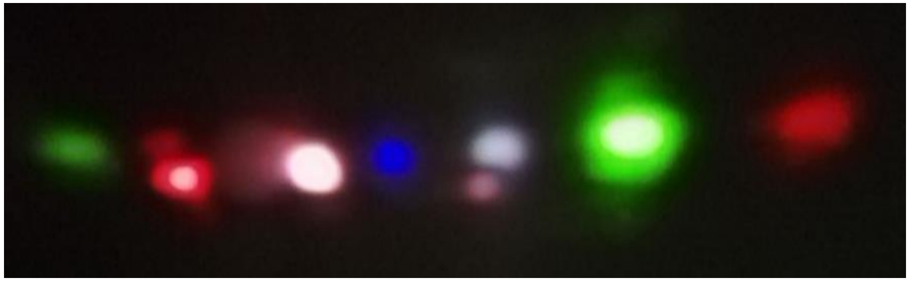
Schematic of Experimental Setup for KTA-OPA





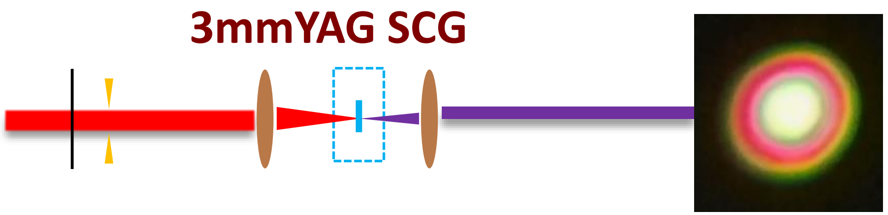
MIR output:

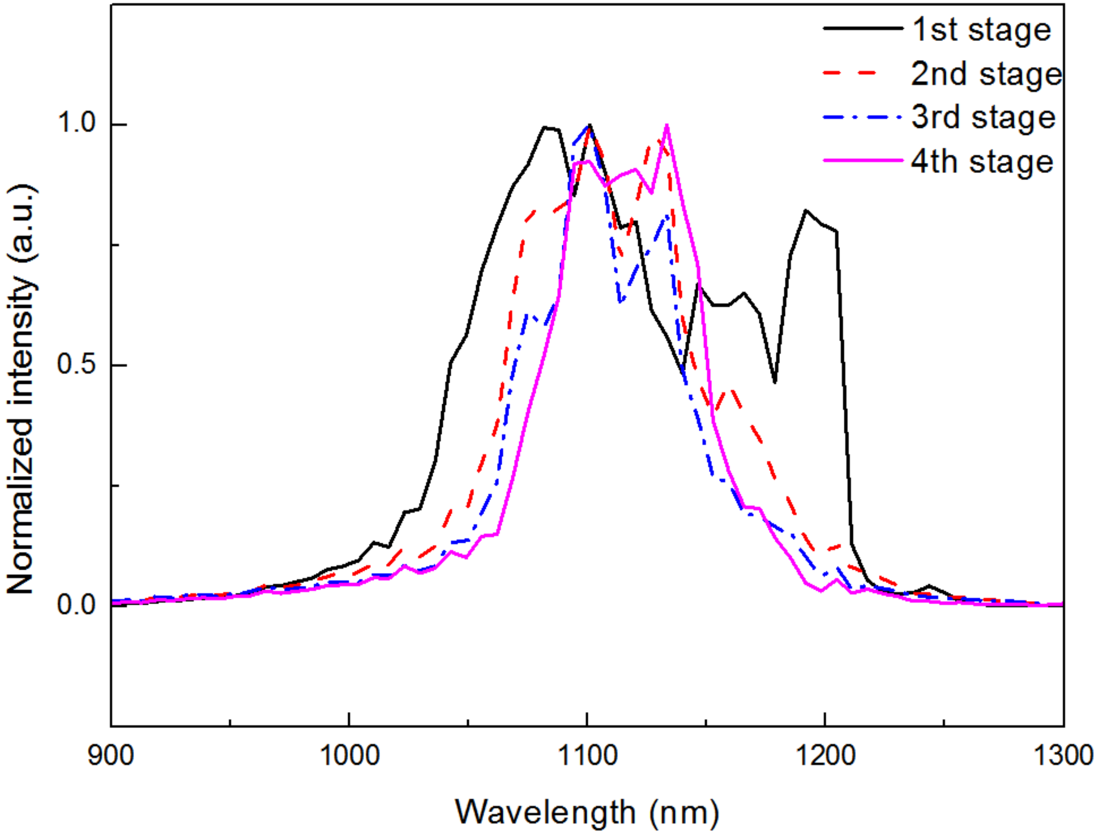
- Center: 2864nm
- FWHM: 525nm
- Energy: 520μJ
- Stability(RMS) ： 1.86%



Signal from 3mm YAG and amplification

Signal from the super-continuum generation by focus the pump laser into the YAG crystal.

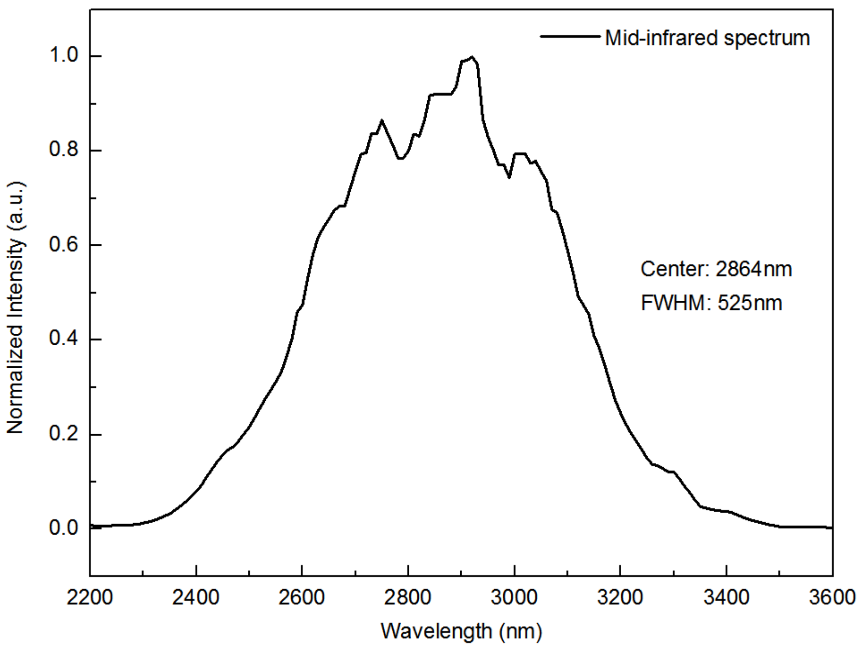


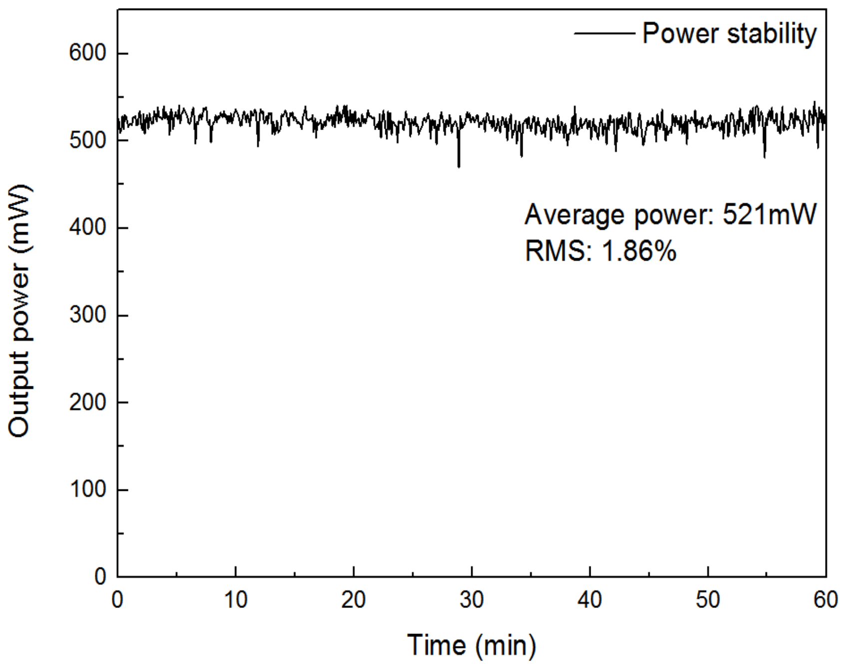


Signal output of the final stage:

- Center: 1115nm
- FWHM: 72nm
- Energy: 1.8mJ (1kHz)

Spectrum and Stability





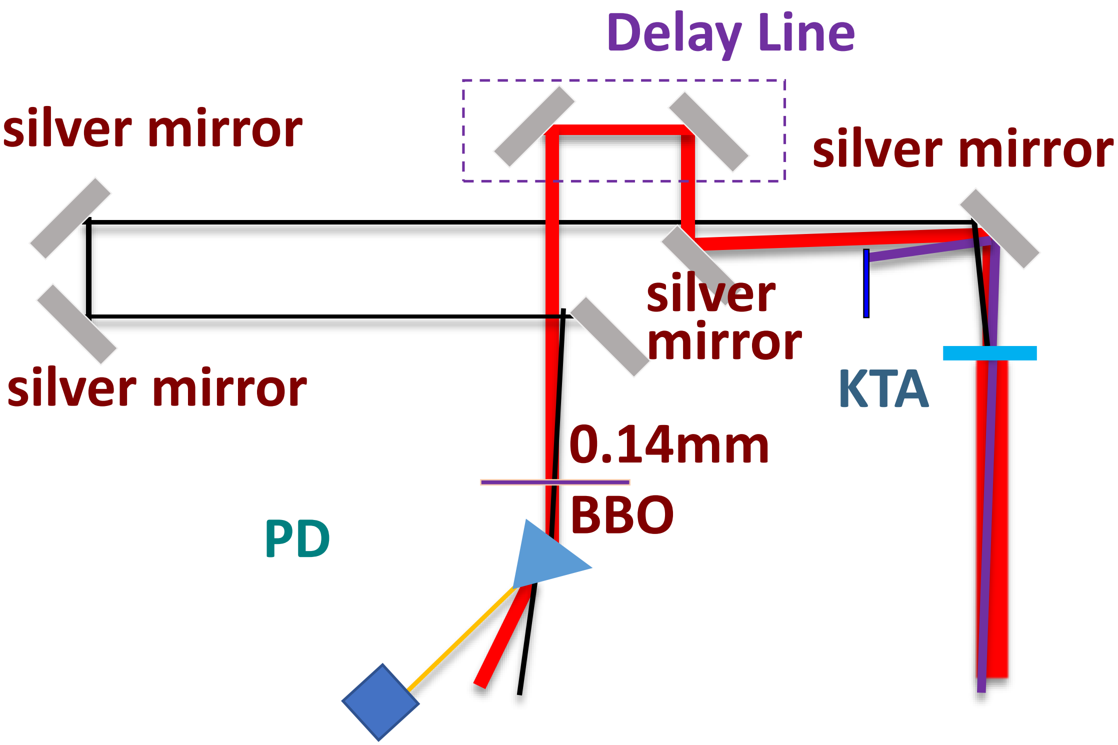
Characteristics

- Center: 2864nm
- FWHM: 525nm
- Energy: 520μJ (1kHz)
- FTL: 27fs

Energy stability (over 1 hour)

- Average power: 521mW (1kHz)
- RMS deviation ：1.86%

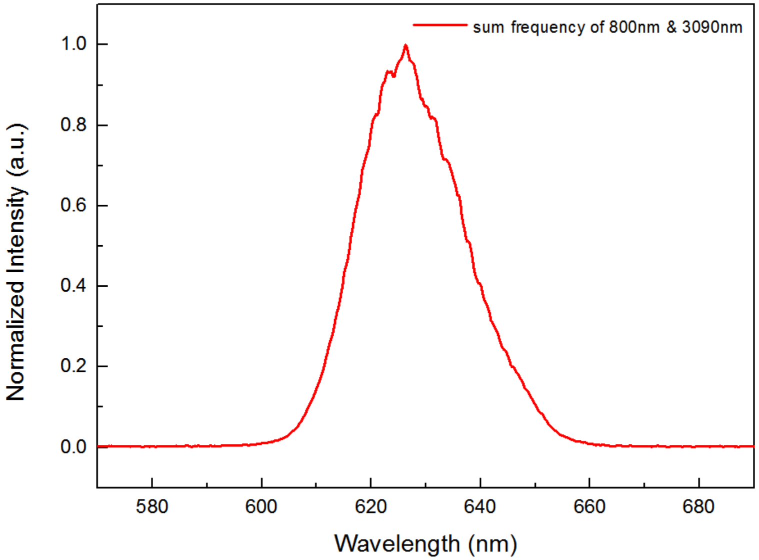
Measurement of laser pulse



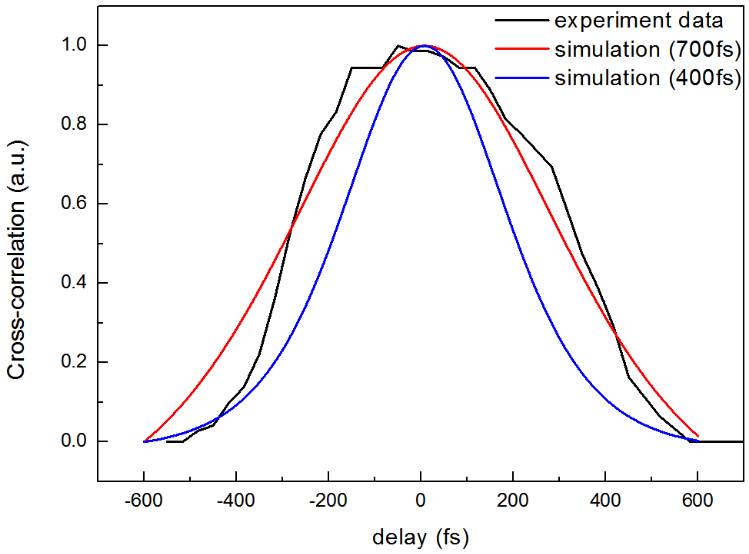
$$I_{626}(\tau) \propto \int_{-\infty}^{+\infty} \sec h^2\left(\frac{t}{\tau_{800}/1.763}\right) \times\left[\sec h\left(\frac{t-\tau}{\tau_{3090}/1.763}\right) \otimes sqr\left(\frac{t}{\delta_{\mathrm{BBO}}\cdot l_c}+\frac{1}{2}\right)\right]^2 dt$$

$$sqr(x)=\begin{cases} 1 & if\ |x|\le \frac{1}{2} \\ 0 & otherwise \end{cases}$$

Measurement of laser pulse

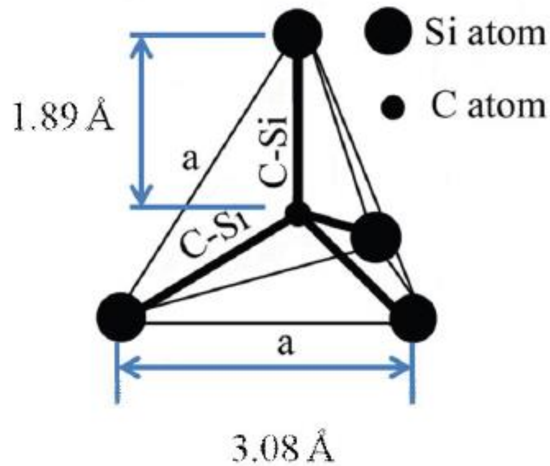


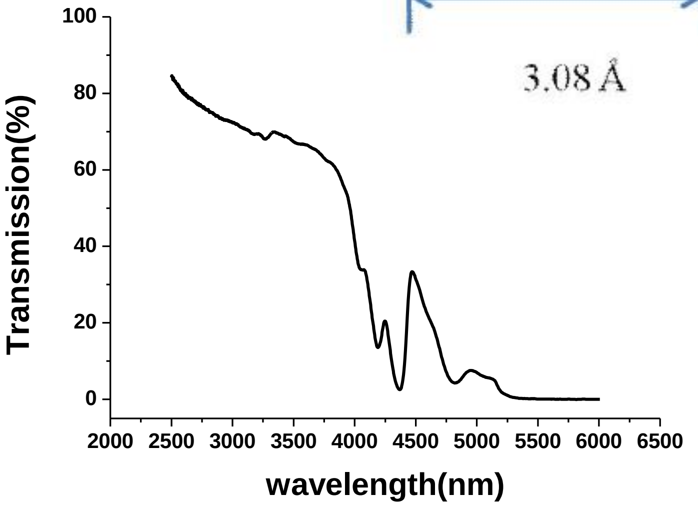
Spectrum of the SFG
(Sum frequency generation)

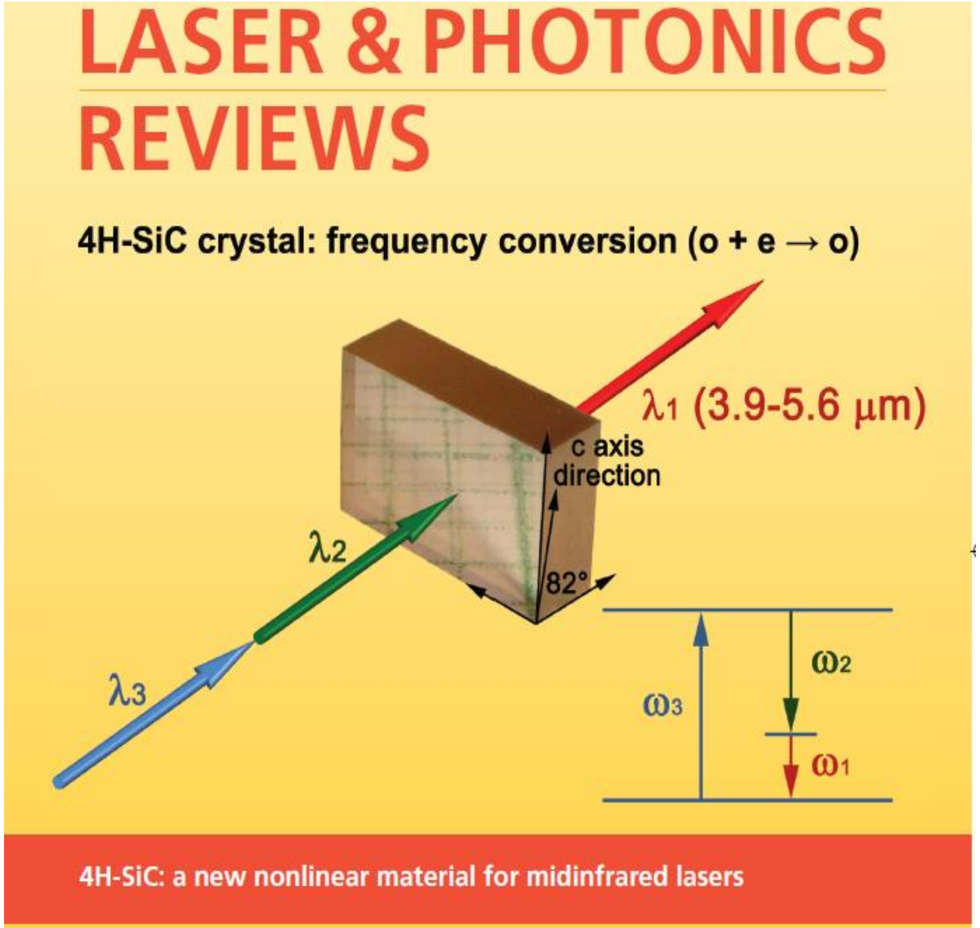


Cross-correlation trace
for pulse duration

SiC-a new crystal for MIR



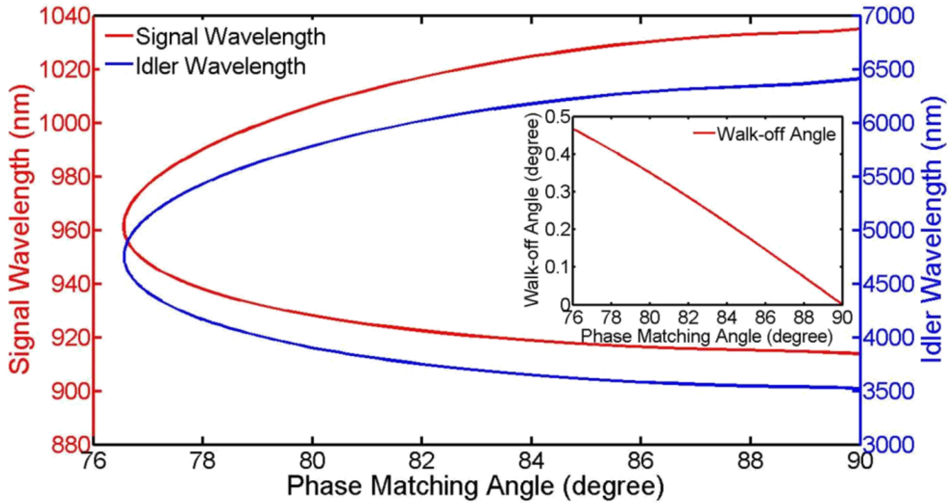




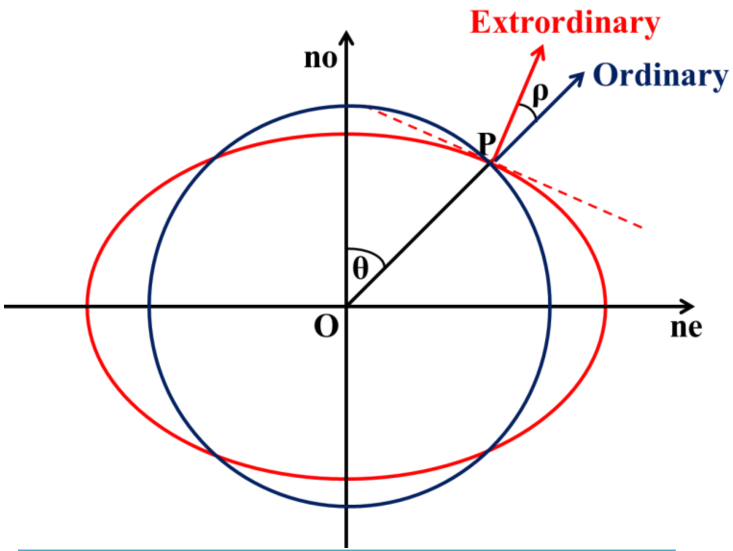
- **High nonlinear coefficient**
- **High damage threshold**
- **Good thermal conductivity**

Shunchong Wang *et al.*, Laser Photonics Rev. Vol.**7**, 831 (2013)

Character of 4H-SiC Crystal



Phase-Matching Curve



Walk-off Angle

Sellmeier Equations

$$n_e^2(\lambda) = 6.79485 + \frac{0.15558}{\lambda^2 - 0.03535} - 0.02296\lambda^2$$

$$n_o^2(\lambda) = 1 + \frac{0.20075\lambda^2}{\lambda^2 + 12.07224} + \frac{5.54861\lambda^2}{\lambda^2 - 0.02641} + \frac{35.65066\lambda^2}{\lambda^2 - 1268.24708}$$

800nm(o) → 1017nm(e)+3750nm(o)

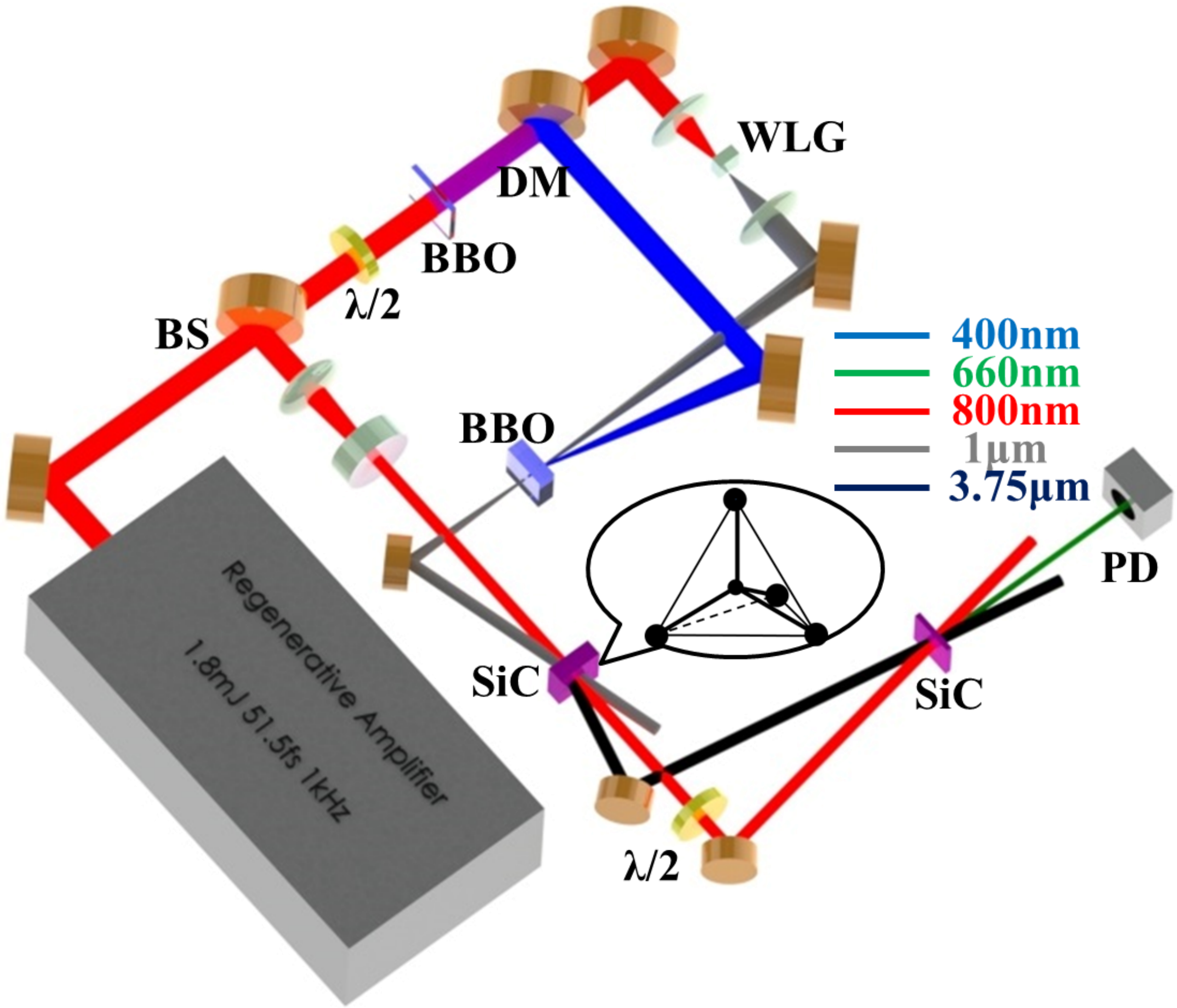
Schematic of Experimental Setup

BBO (SHG)
1mm 29.2°

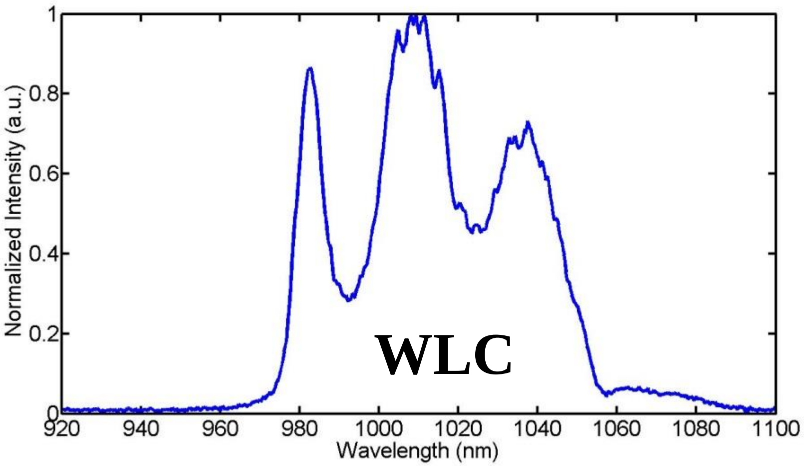
BBO (OPA)
3mm 28.6°

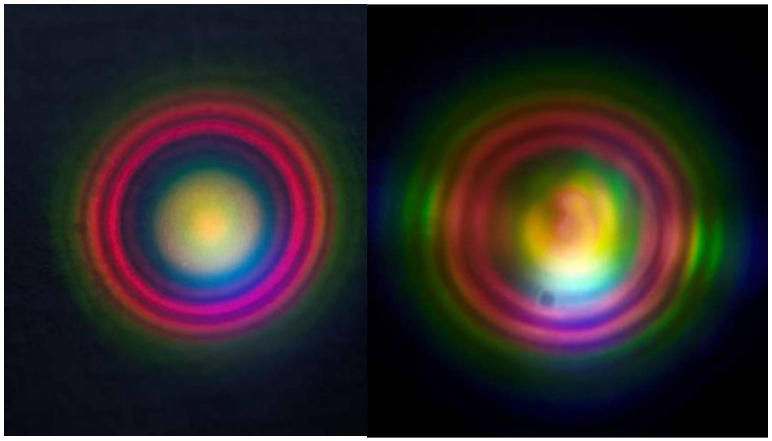
SiC (OPA)
3mm 90°

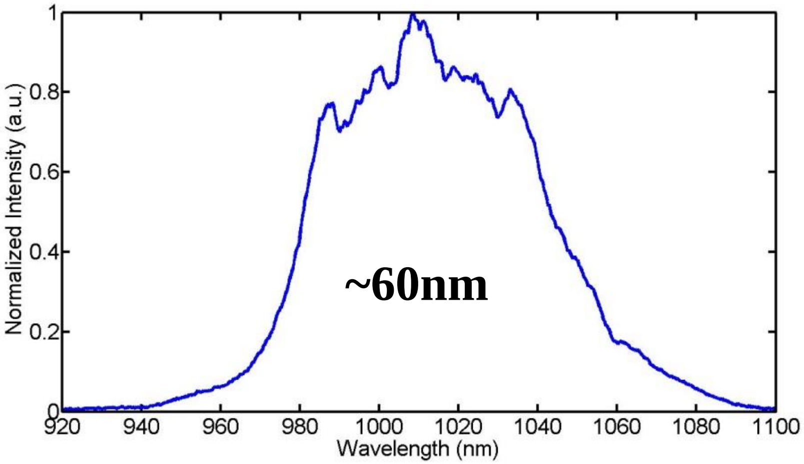
SiC (SFG)
1mm 90°



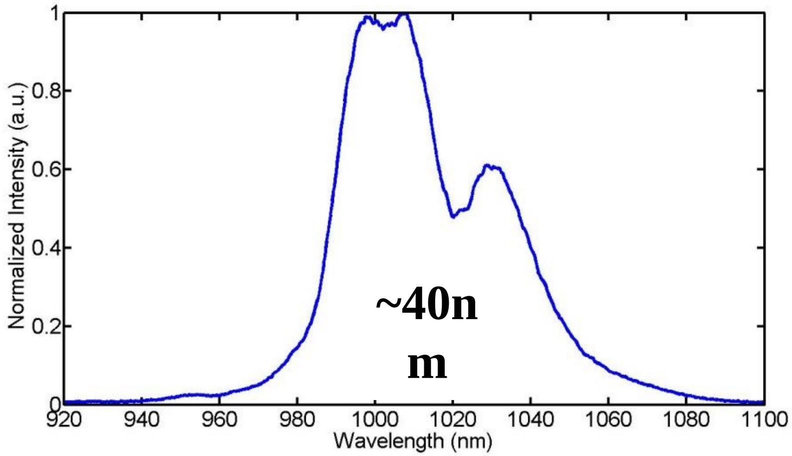
Results and Pulse Characterization





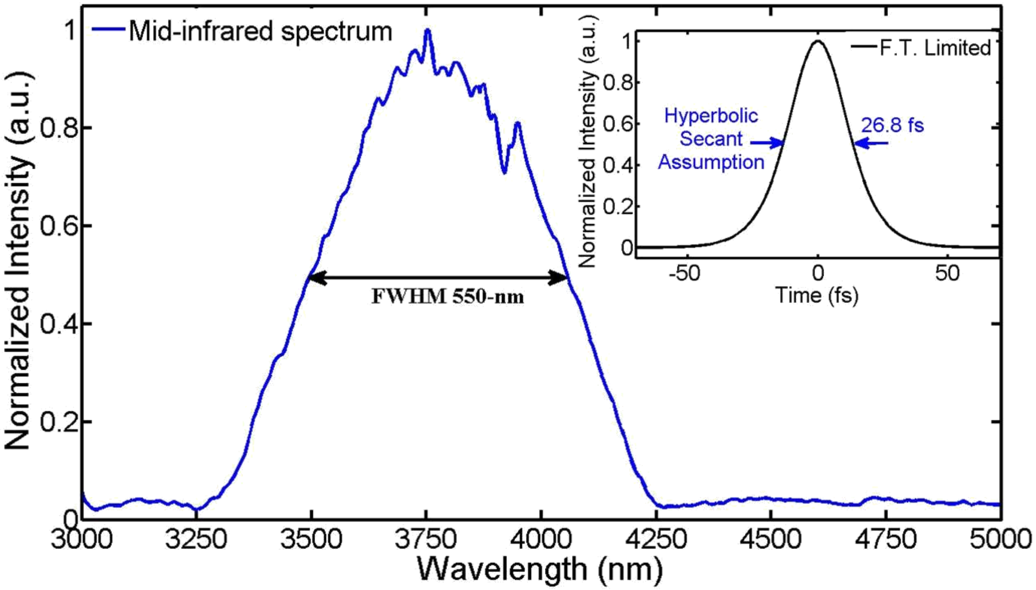


1st OPA



2nd OPA

Results and Pulse Characterization

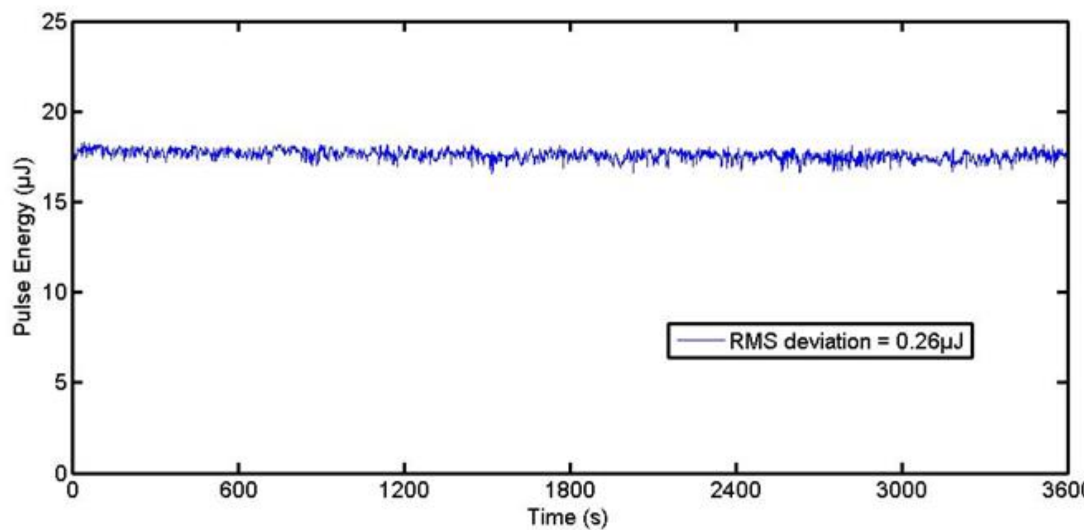


Spectrum: 550nm

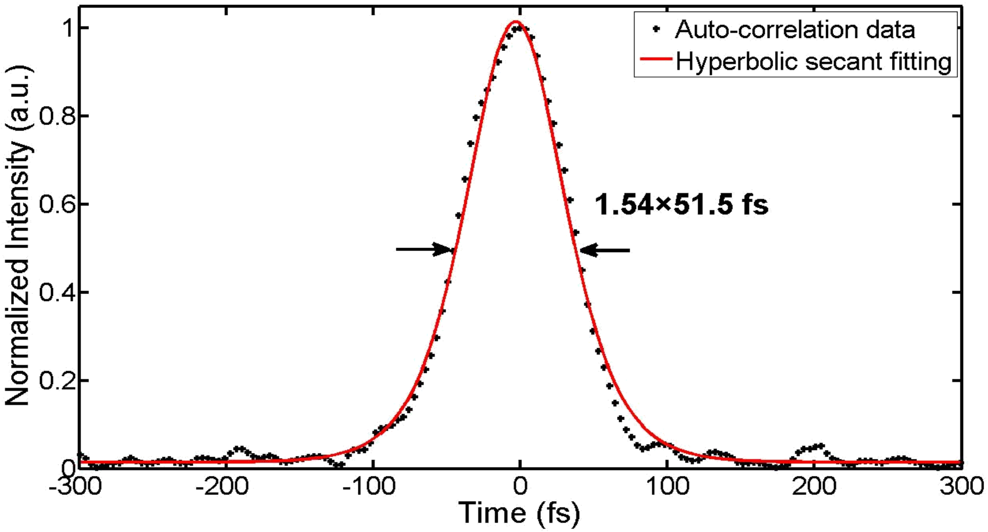
FT Limit: 26.8-fs

Energy 17 μJ

RMS = 1.48%



Results and Pulse Characterization



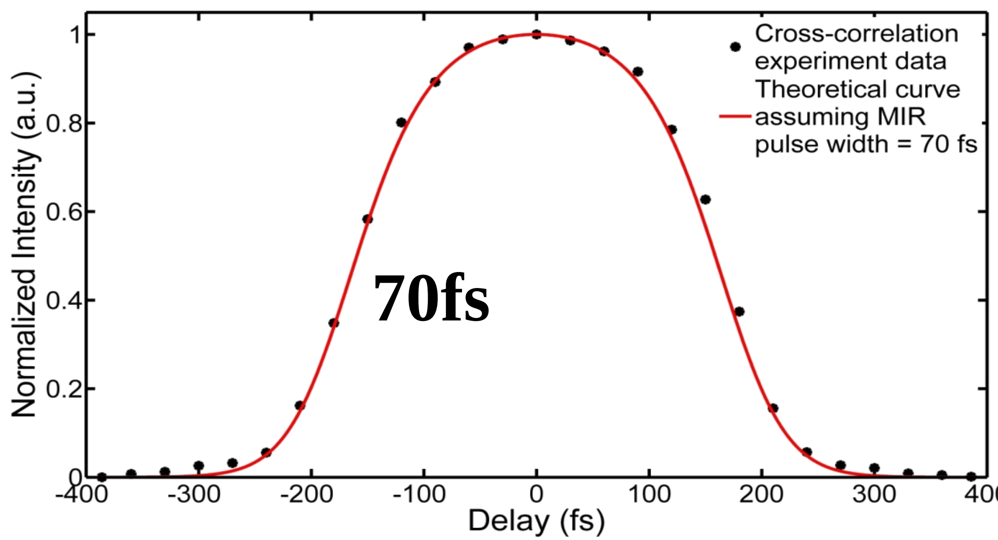
Since the low energy， we measured the pulse duration by using cross-correlator

$$I_{660}(\tau) \propto \int_{-\infty}^{+\infty} sech^2\left(\frac{t}{\tau_{800}/1.763}\right) \times \left[sech\left(\frac{t-\tau}{\tau_{3750}/1.763}\right) \otimes sqr\left(\frac{t}{\delta_{si} l_c} + \frac{1}{2}\right)\right]^2 dt$$

$$sqr(x) = \begin{cases} 1 & \text{if } |x| \leqslant \frac{1}{2}, \\ 0 & \text{otherwise.} \end{cases}$$

Cross-Correlation Curve assuming 70fs MIR and 50fs NIR

Hai-Tao Fan, et al *Opt Lett* **39** 6249(2014)



Outline

- ➢ **General Introduction**
- ➢ **Ultrahigh Intensity Laser-Toward multi-PW power**
  - ◆ **Oscillator-Generation of femtosecond laser**
  - ◆ **Stretcher-Management of dispersion**
  - ◆ **Amplifier-Boost laser energy**
  - ◆ **Compressor-compensate dispersion for high peak power**
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  - ◆ **Typical PW laser facilities in the world**
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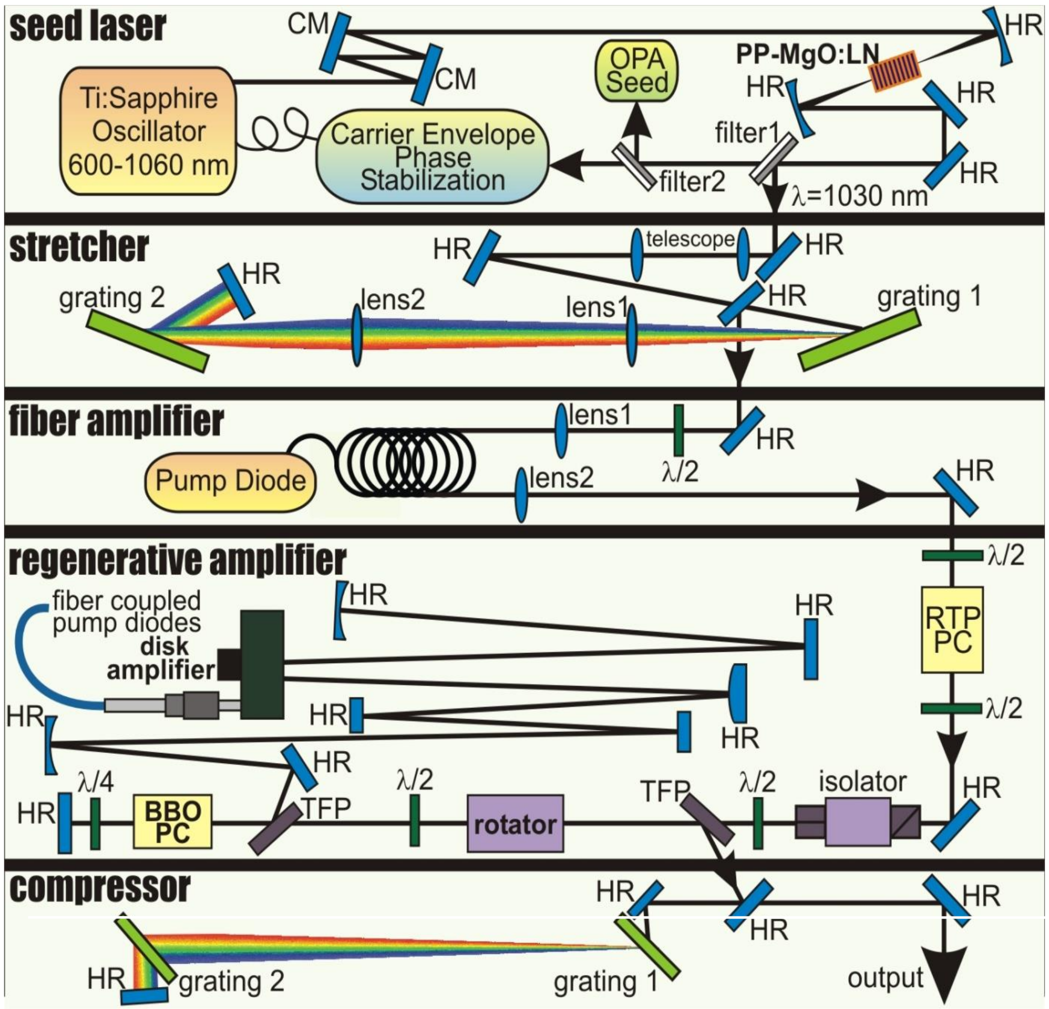
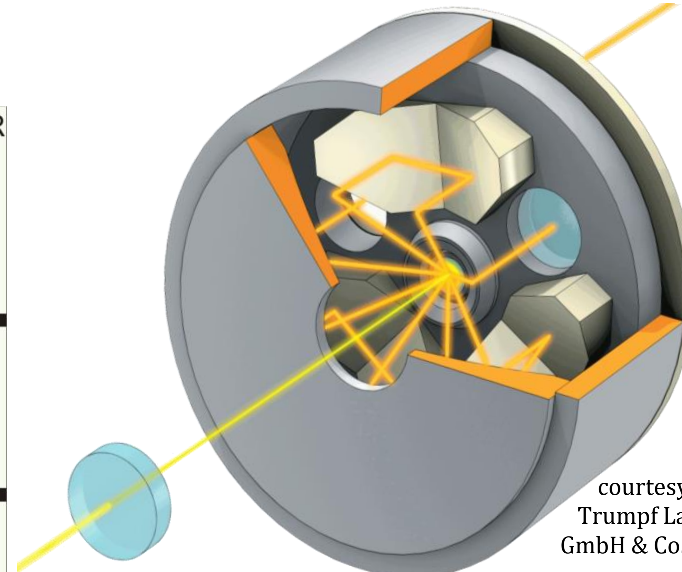
- ➢ **Optical Parametric Amplifier-Toward mid-infrared range**
- ➢ **High average power-Toward All-Solid State Amplifier**
- ➢ **Acknowledgement**

Next generation-thin disc femtosecond laser

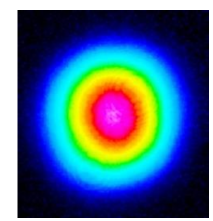
Lasersystem – Yb:YAG thin-disc regenerative amplifier





courtesy of:
Trumpf Laser
GmbH & Co. KG

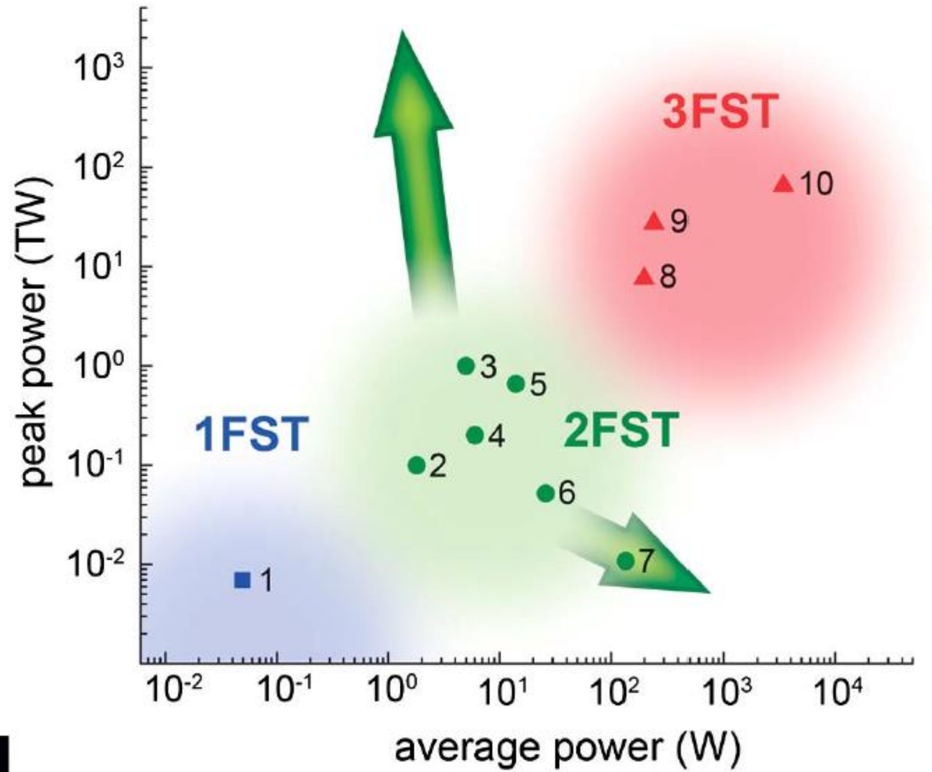
Regenerative amplifier:
(Laserhead Trumpf Laser)



Number of round trips	150
Repetition rate	1-10 kHz
Pulse enrgy	25 mJ
Average power	75W
Pulse duration	1.6 ps
Bandwidth	~ 1 nm

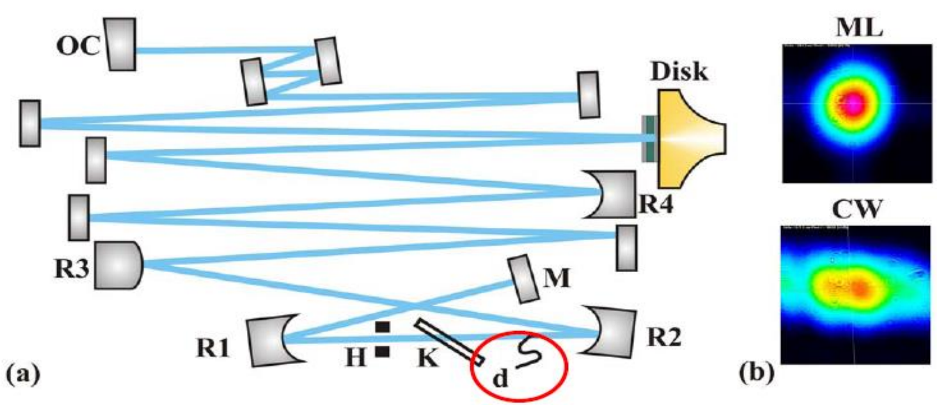
Status and trend of mode-locking disk laser

	Power & Energy
SESAM (ETH, 2012)	275 W, 25.6 MW, 583 fs, 16.9 μJ, 16 MHz (Vacuum)
SESAM (ETH, 2014)	242 W, 66 MW, 1.07ps, 80 μJ, 3 MHz (Vacuum)
KLM (MPQ, 2011)	17 W, 1.7 MW, 200fs 0.43 μJ, 40 MHz (air)
KLM (MPQ, 2014)	270 W, 38 MW, 330fs 14.4 μJ, 19 MHz (air)



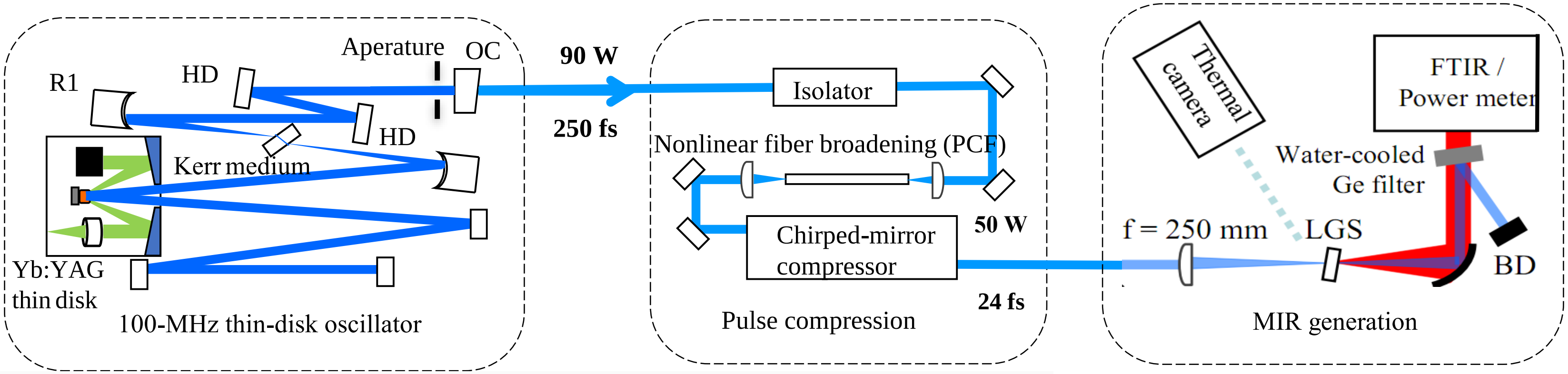
	τ_{pulse}	E_{pulse}	P_{peak}	$P_{average}$
system 8	5 fs	40 mJ	7.5 TW	200 W
system 9	1.7 fs	49 mJ	27 TW	245 W
system 10	5 fs	345 mJ	65 TW	3450 W

H.Fattahi et al, Optica,1.45(2014)

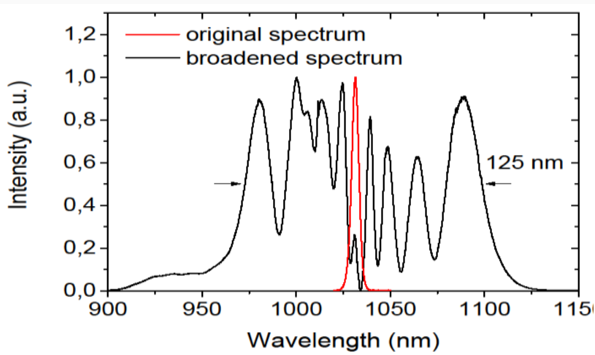


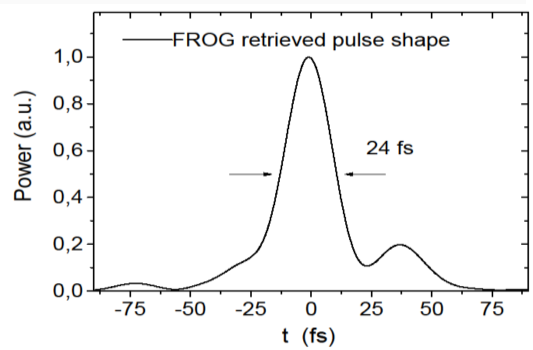
OL 36(24) 4746 (2011)

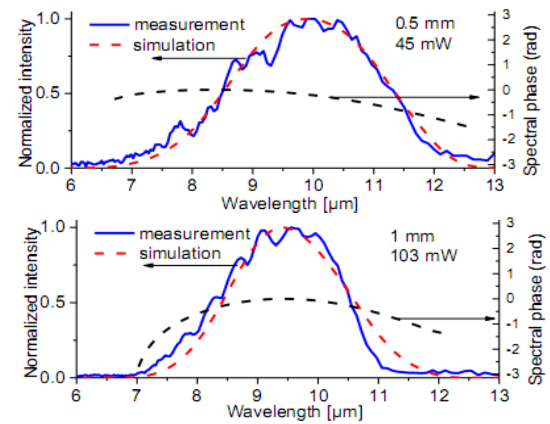
Thin disc Yb:YAG laser at 100MHz



- 100 MHz KLM oscillator--90 W, 250 fs/50W, 24 fs
- 200 MHz KLM oscillator--75 W, 260 fs







J Wei et al, Opt Express, Vol. 21: 29867 (2013)
J Wei et al, Opt Lett. Vol.40:1627 (2015)

I. Pupeza, et al.,
CLEO Postdeadline, STh5C, 2014

Innoslab femtosecond amplifier

OPTICS EXPRESS 2009 / Vol. 17, No. 15 12230

400 W Yb:YAG Innoslab fs-amplifier

P. Russbueldt[1,*], T. Mans[1], G. Rotarius[1], J. Weitenberg[2], H.D. Hoffmann[1] and R. Poprawe[1,2]

[1] *Fraunhofer Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany*

OPTICS LETTERS 2010 / Vol. 35, No. 24 4169

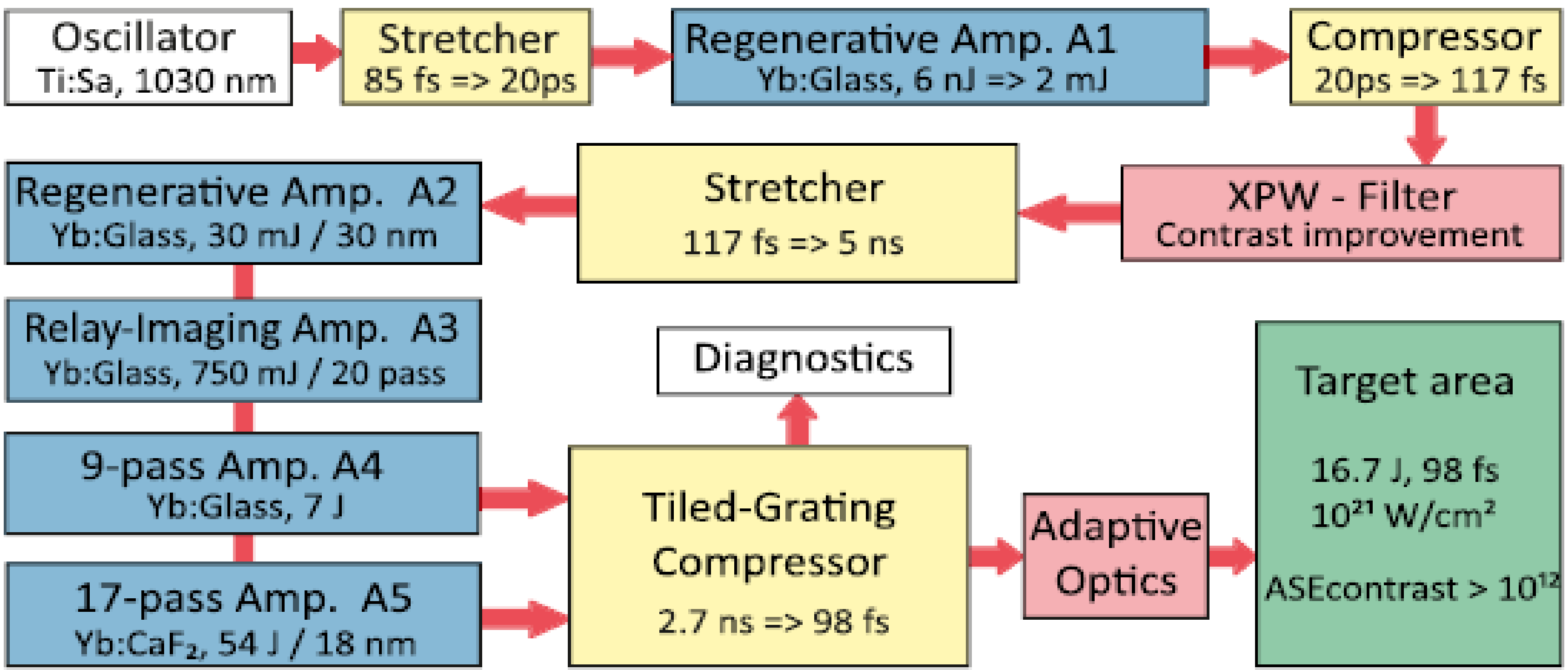
Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier

P. Russbueldt,[1,*] T. Mans,[2] J. Weitenberg,[2] H. D. Hoffmann,[1] and R. Poprawe[1,2]

[1] *Fraunhofer Institute for Laser Technology, Steinbachstrasse 15, 52074 Aachen, Germany*

POLARIS laser system

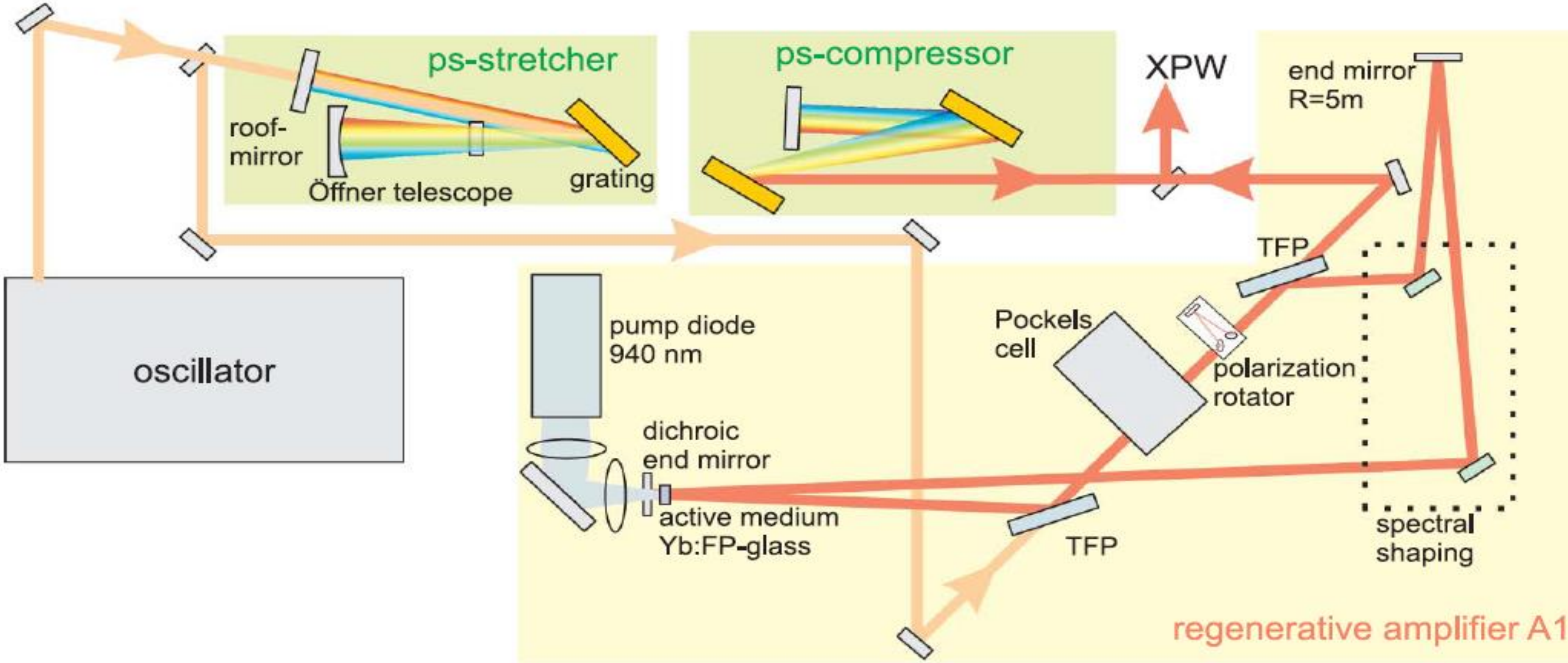
Petawatt **O**ptical **L**aser **A**mplifier for **R**adiation **I**ntensive Experiment**S**



- **Institute for Optics and Quantum Electronics Jena**
- **Helmholtz-Institute Jena**

DCPA design（ps，ns)
A1-A2：Regenerative amp
A3: image relay multi-pass amp（20pass)
A4：9 pass amp
A5：17 pass amp（54J/26.6.J)

POLARIS laser system



A1 （output: 2mJ，1Hz)

◆ Seeding：75MHz ,85fs (Ti:Sa)@1030nm

◆ Pump laser: laser diode@940nm

◆ Gain crystal：Yb:Glass

◆ Cavity configuration: Ring regenerative amp with function to control gain narrowing effect (from 12nm to 16nm)

A2（output: 30mJ)
Same design with A1

Letter Vol. 41, No. 22 / November 15 2016 / Optics Letters 5413

Optics Letters

54 J pulses with 18 nm bandwidth from a diode-pumped chirped-pulse amplification laser system

Marco Hornung,[1,2,*] Hartmut Liebetrau,[2] Sebastian Keppler,[2] Alexander Kessler,[1] Marco Hellwing,[2] Frank Schorcht,[1] Georg A. Becker,[2] Maria Reuter,[2] Jens Polz,[2] Jörg Körner,[2] Joachim Hein,[1,2] and Malte C. Kaluza[1,2]

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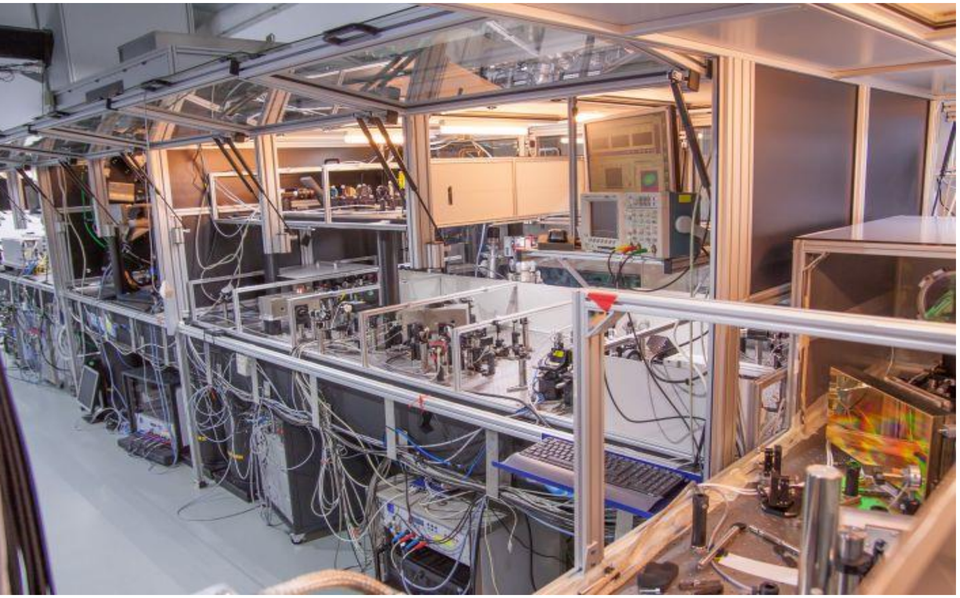
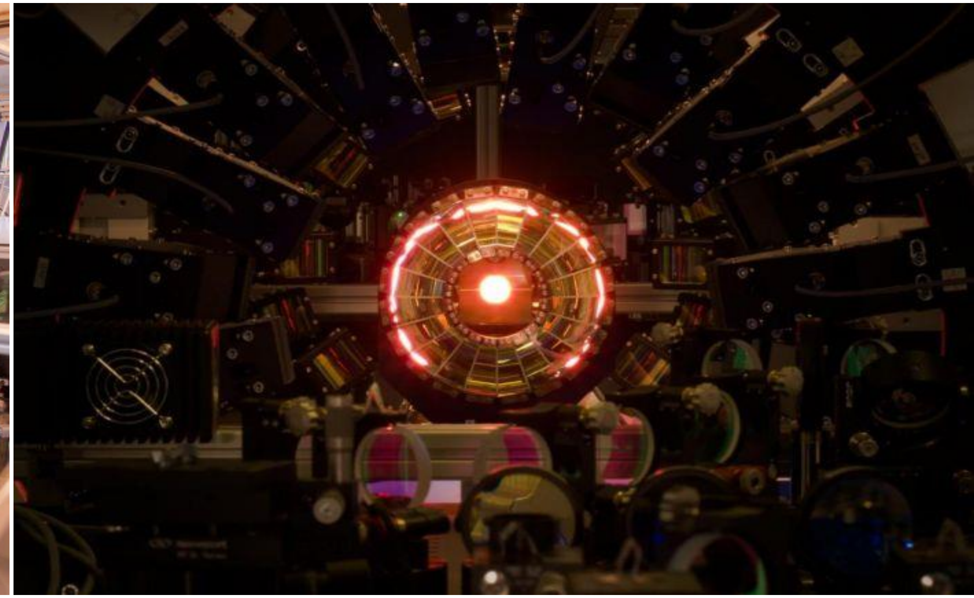
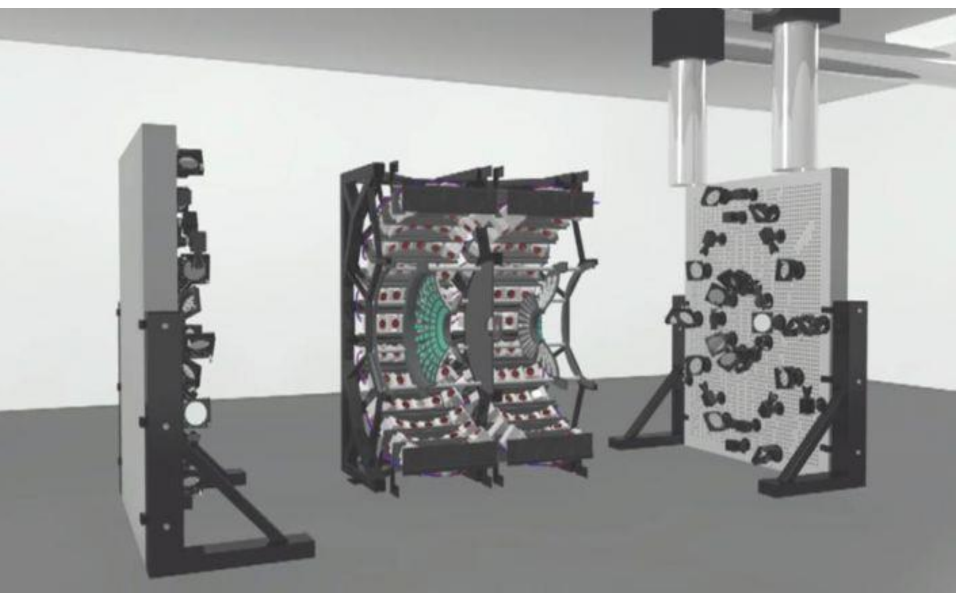
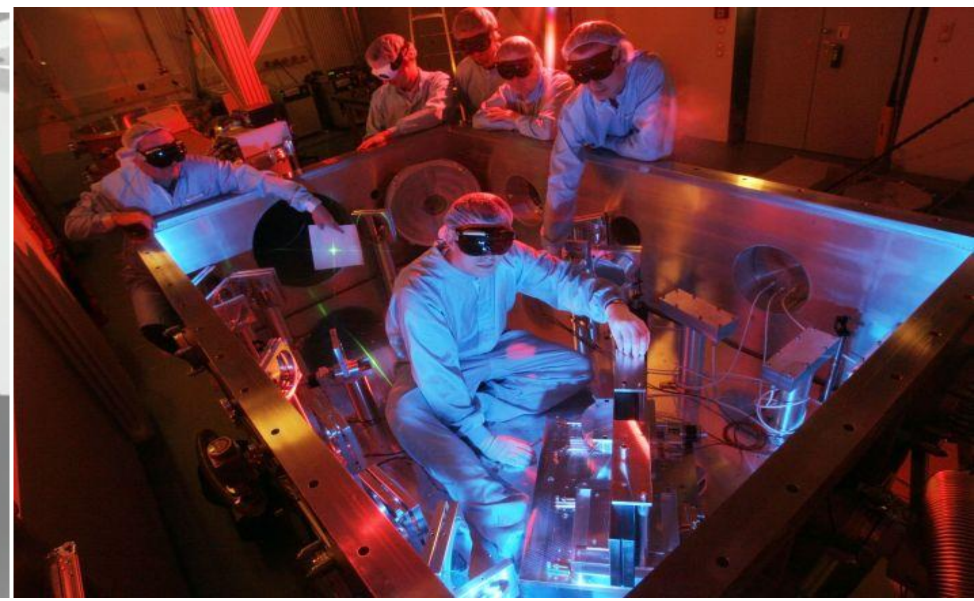
Repetition rate: 1/50 Hz
Energy: 54J (before compressor)
16.7J(after compressor)
Pulse duration: 98fs
Peak power: ~200TW
10^{12} contrast

Summary

- General Introduction
- Ultrahigh Intensity Laser-Toward multi-PW power
  - Oscillator-Generation of femtosecond laser
  - Stretcher-Management of dispersion
  - Amplifier-Boost laser energy
  - Compressor-compensate dispersion for high peak power
  - Enhancement on contrast ratio
  - Typical PW laser facilities in the world
- Ultrafast Laser-Toward Few Cycles and Attosecond Pulse
- Optical Parametric Amplifier-Toward mid-infrared range
- High average power-Toward All-Solid State Amplifier
- Acknowledgement

Acknowledgement

My Colleagues and Students at IoP/CAS, Xidian U

Welcome visit our website: http://ultralaser.iphy.ac.cn/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➢ Laser applications in medicine & biology
➢ Terahertz generation and applications
➢ Nonlinear optics and quantum optics
➢ Ultra-high intensity lasers
➢ Laser material processing
➢ Advanced laser materials

Thank you for your attention！