Recent progress in ultrafast intense laser development and high field laser physics research at SIOM

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Chinese Academy of Sciences, China

SIOM
中国科学院上海光学精密机械研究所

ICUIL2008, Oct.27-31, 2008, Tongli Lake, China

Outline: two lasers and two experiments

1. *Motivation*
2. *Harmonic generation in a shaped laser field by using a few cycle laser driver* *(as session)*
3. *Table-top fusion of cluster target driven by sub-petawatt laser pulses* *(u-h meeting)*
4. *Conclusions*

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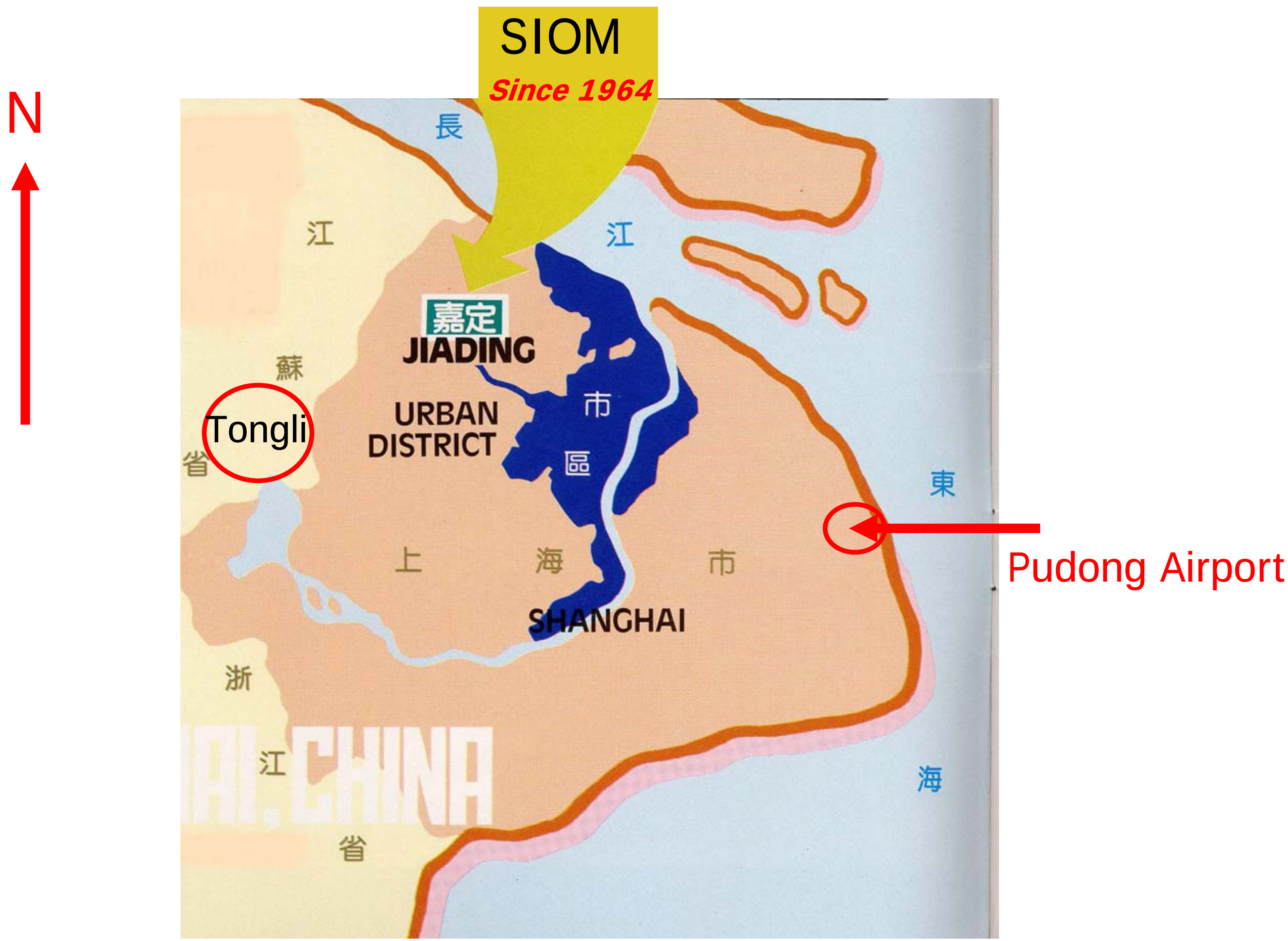
Map of China

Xinjiang
Tibet
Qinghai
Gansu
Inner Mongolia
Ningxia
Heilongjiang
Jilin
Liaoning
BEIJING
Tianjin
Hebei
Shanxi
Shandong
Shaanxi
Henan
Jiangsu
Shanghai
Sichuan
Chongqing
Hubei
Anhui
Zhejiang
Jiangxi
Hunan
Guizhou
Fujian
Yunnan
Guangxi
Guangdong
Hong Kong
Taiwan
Hainan
Islands of South China Sea
Islands of South China Sea
SIOM
Since 1964



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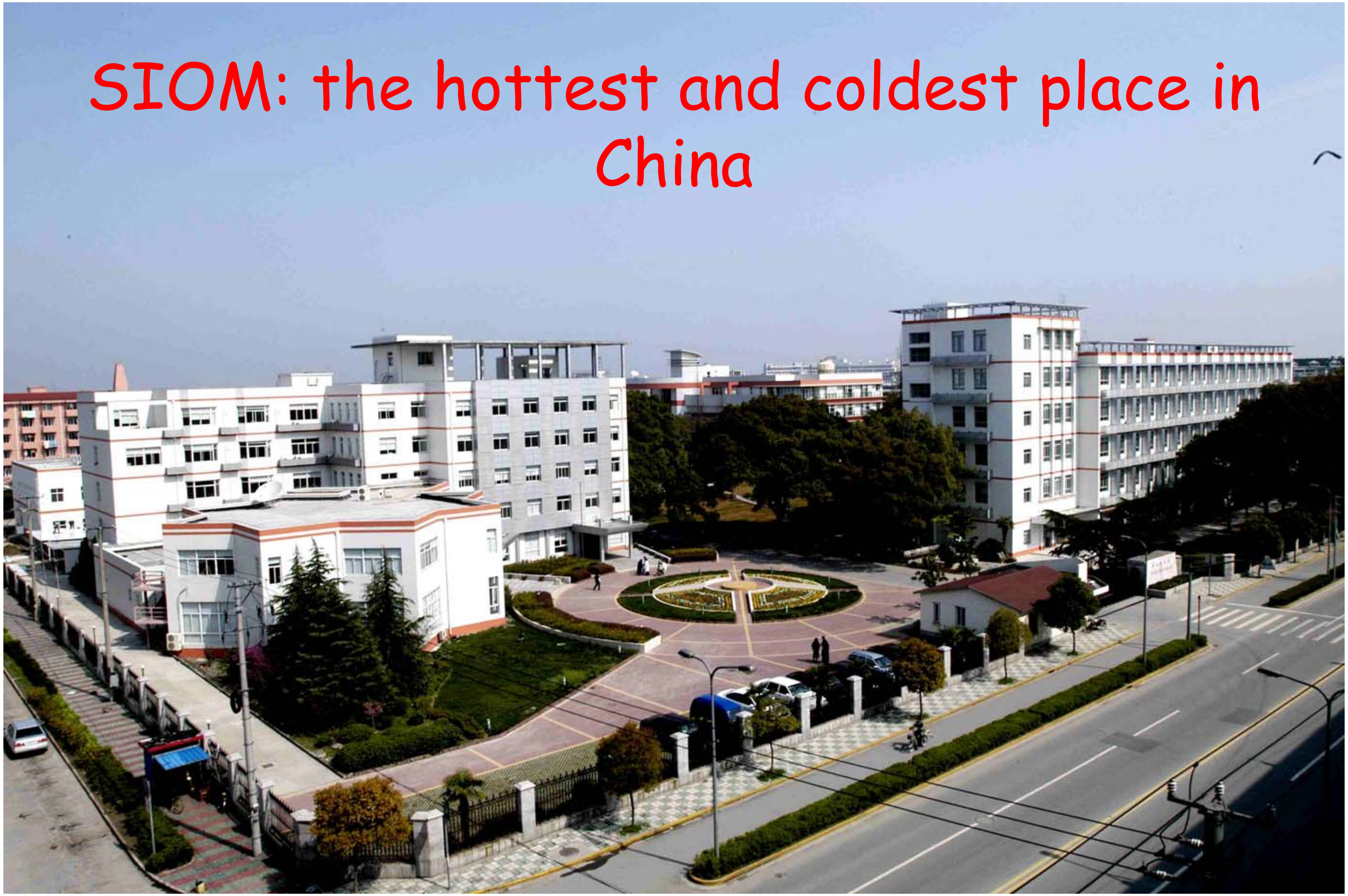
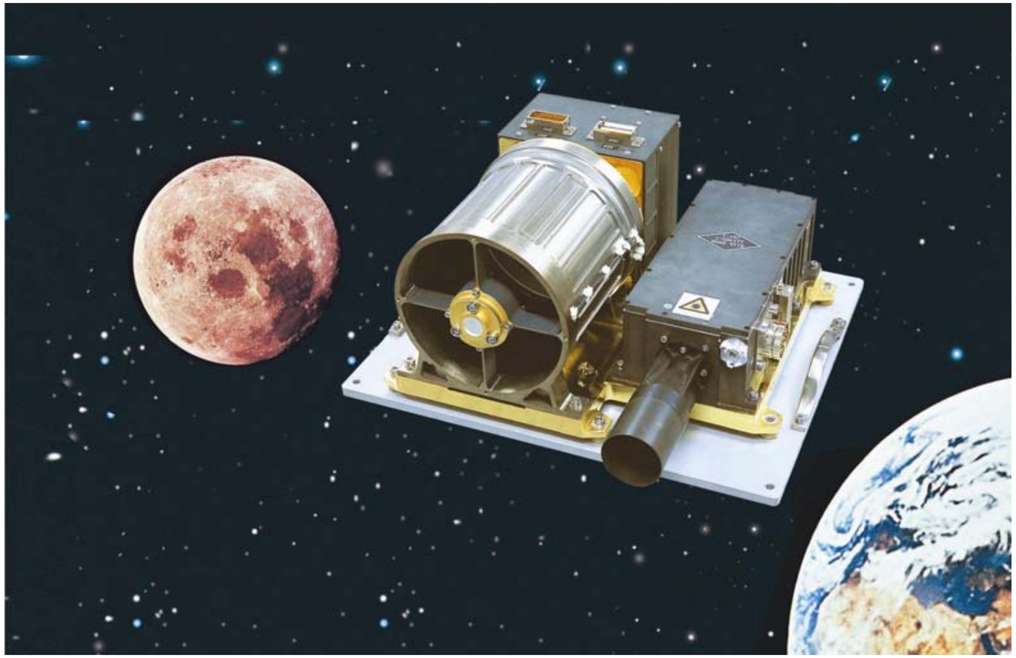
SIOM: the hottest and coldest place in China

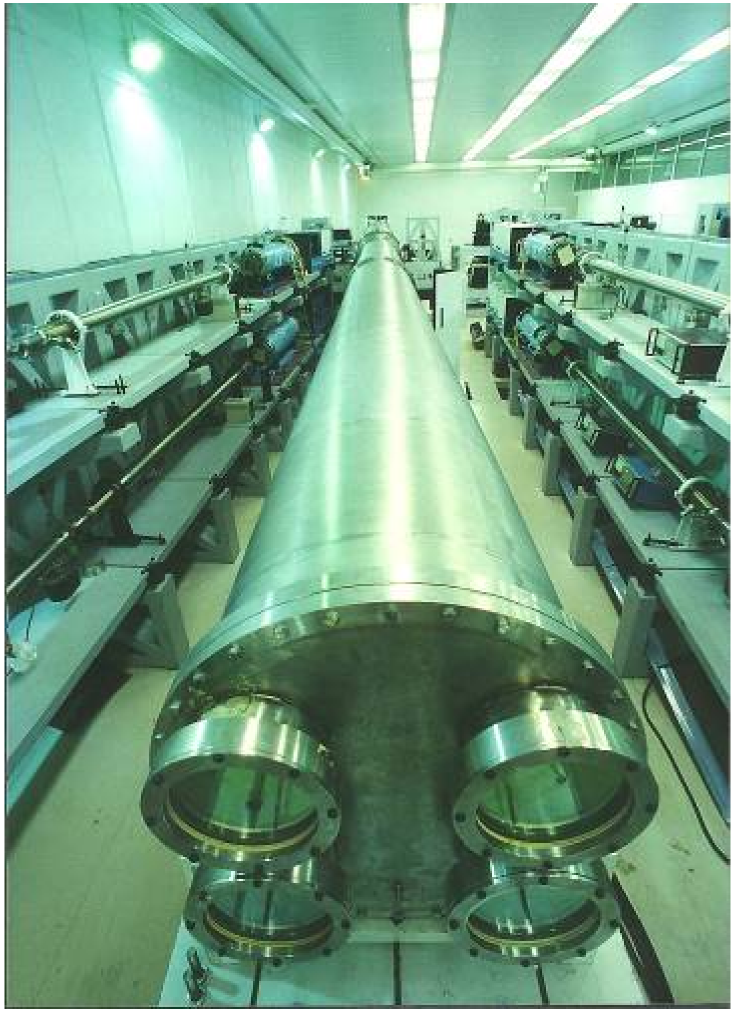


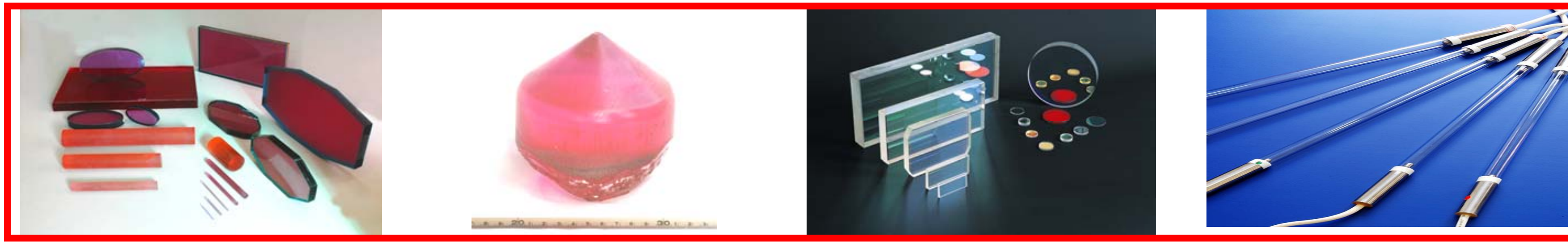
the hottest: laser fusion plasma (million K)

the coldest: laser cooled atoms and BEC (nano K)

First space-laser on the “Moon Exploring satellite” launched in 2007







Laser glass, crystal, coatings, mirrors and flash lamps

Main Research Fields:

- Physics and technology of ultra-fast ultra-intense light sources
- Ultra-fast high-field laser physics
- Basic physics of related high-tech fields: fast ignition, laser accelerator etc.
- Ultra-fast processes and basic research in interdisciplinary fields.

Roadmap of ultrafast intense laser development in SIOM

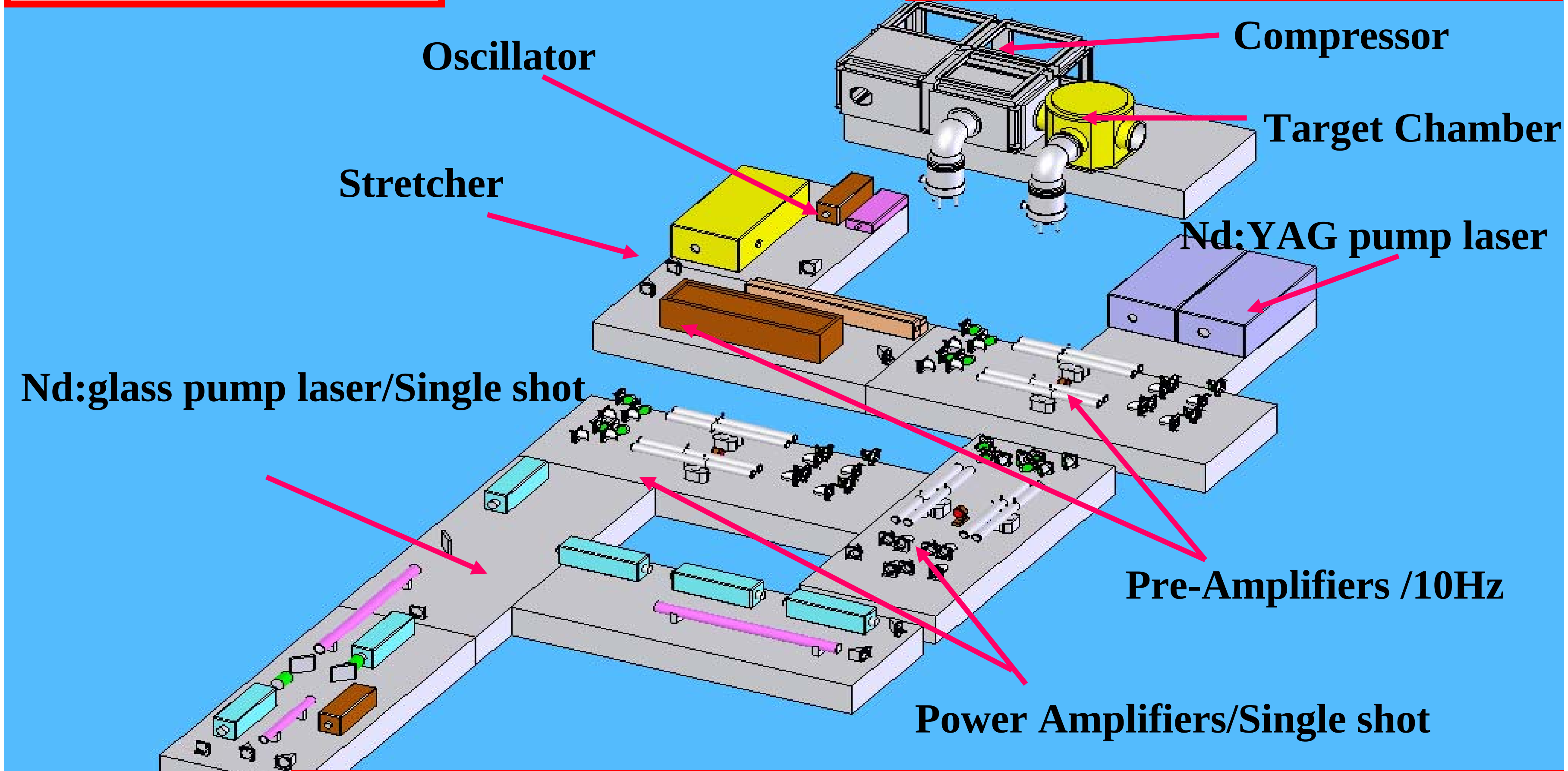
0.7mJ/5fs, 800nm, (2006)

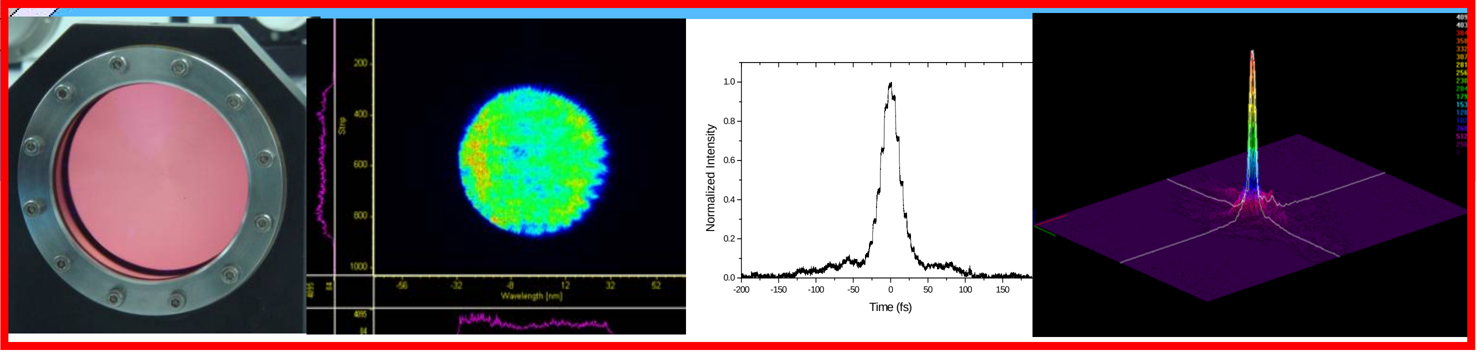
Shorter pulse and longer wavelength IR

Shanghai fs PW Laser system

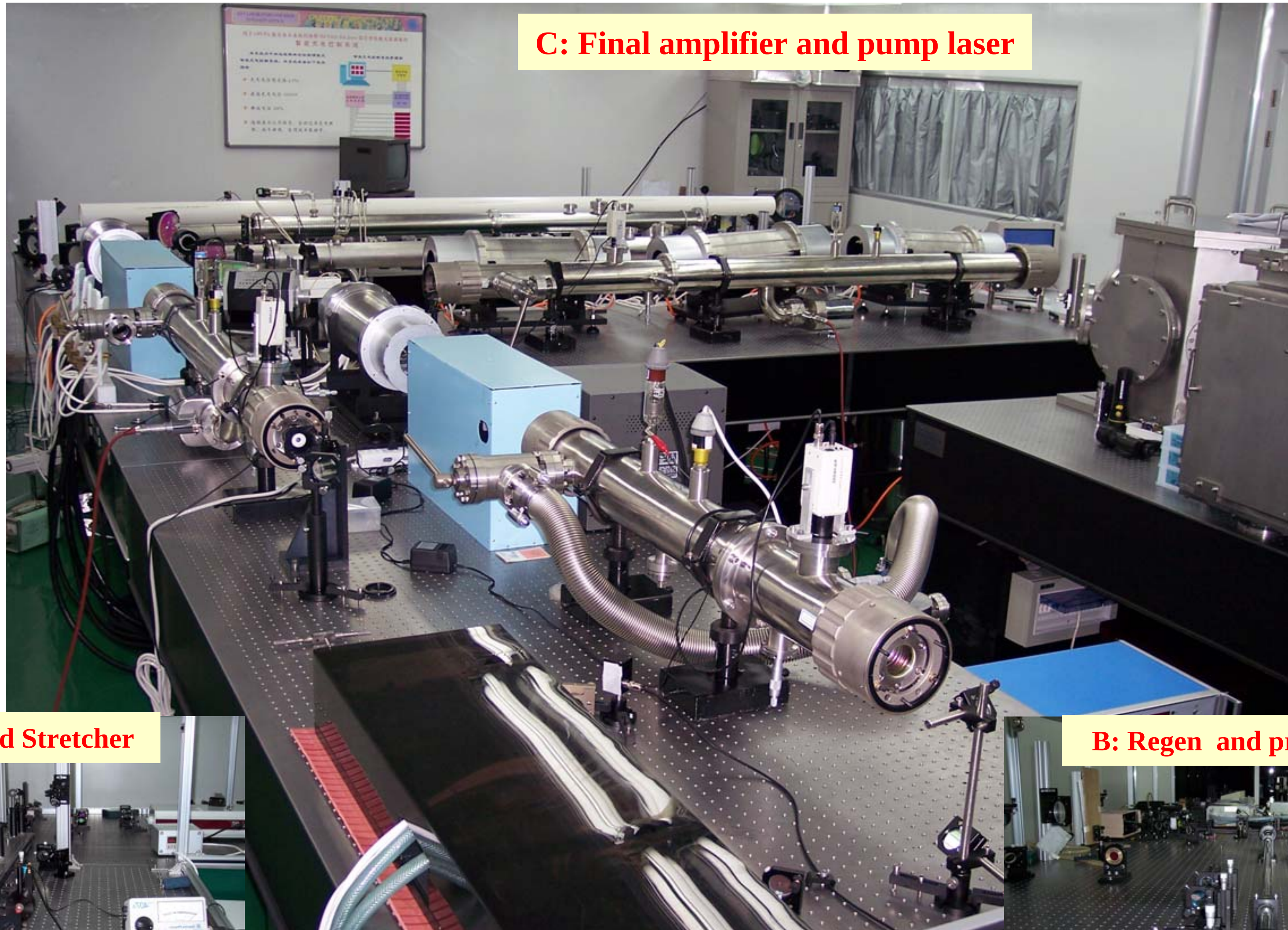
25.8J/29fs, 890TW

Opt. Express 15, 15335 (2007)



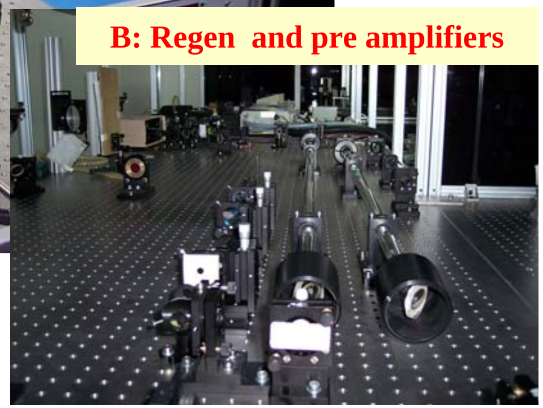


Shanghai fs PW Laser system (25.8J / 29.0fs, 890TW)



C: Final amplifier and pump laser

A: Oscillator and Stretcher

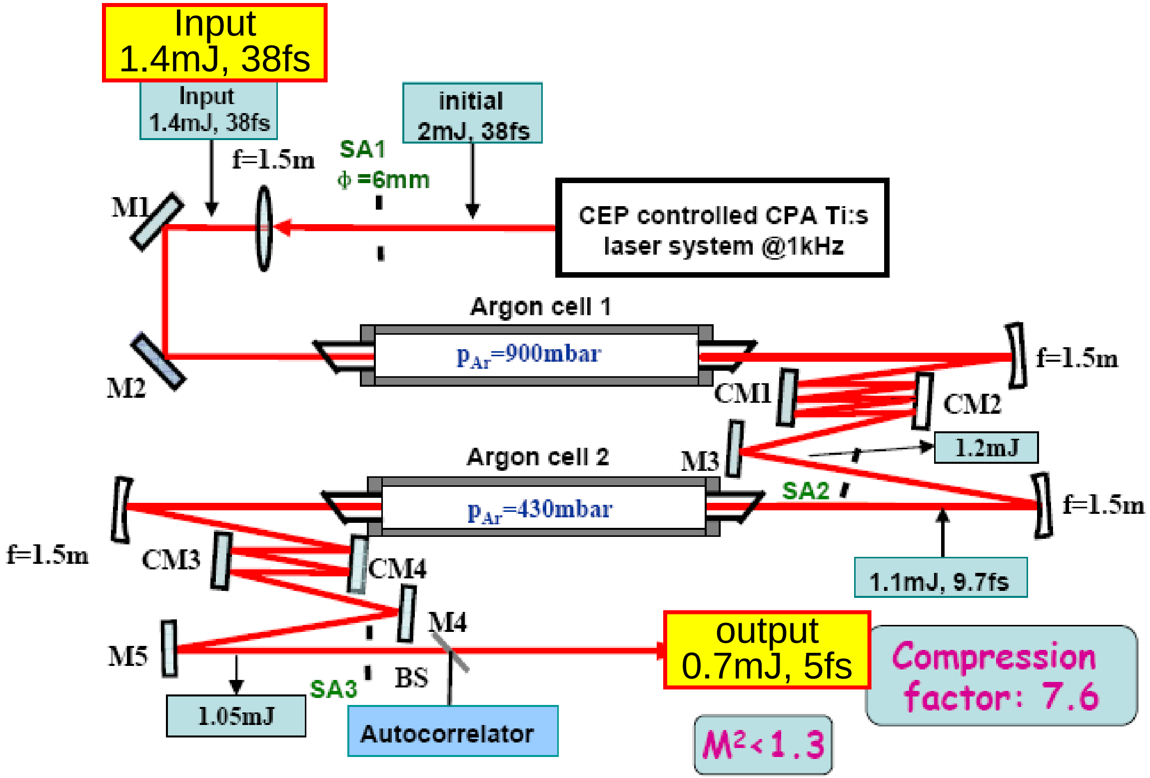


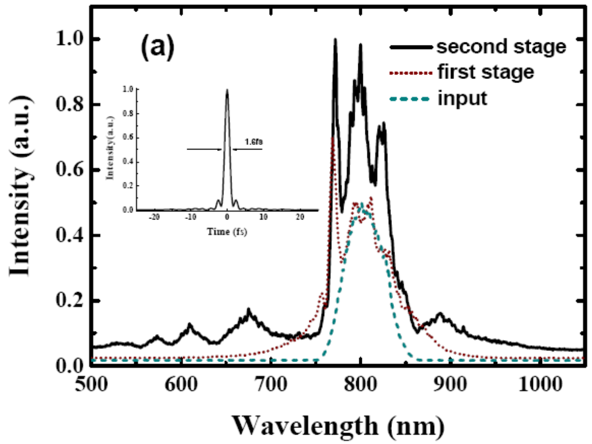
B: Regen and pre amplifiers

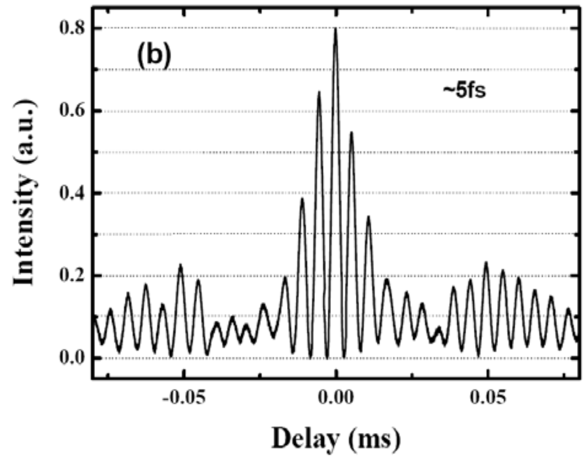
Shanghai fs PW laser target chamber

0.7mJ/5fs, 1kHz laser system

Opt. Lett. 32, 2402(2007)



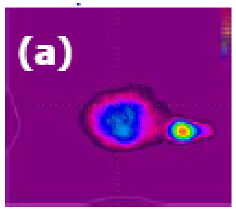




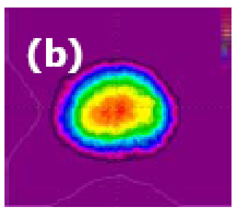
Spectrum (a) and auto-correlation signal (b) of the compressed pulses

Multi-filament control and diffraction suppress by using a soft aperture

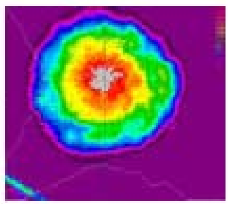
First filament



no aperture



soft aperture



soft aperture

Second filament

New generation of coherent X-ray radiation

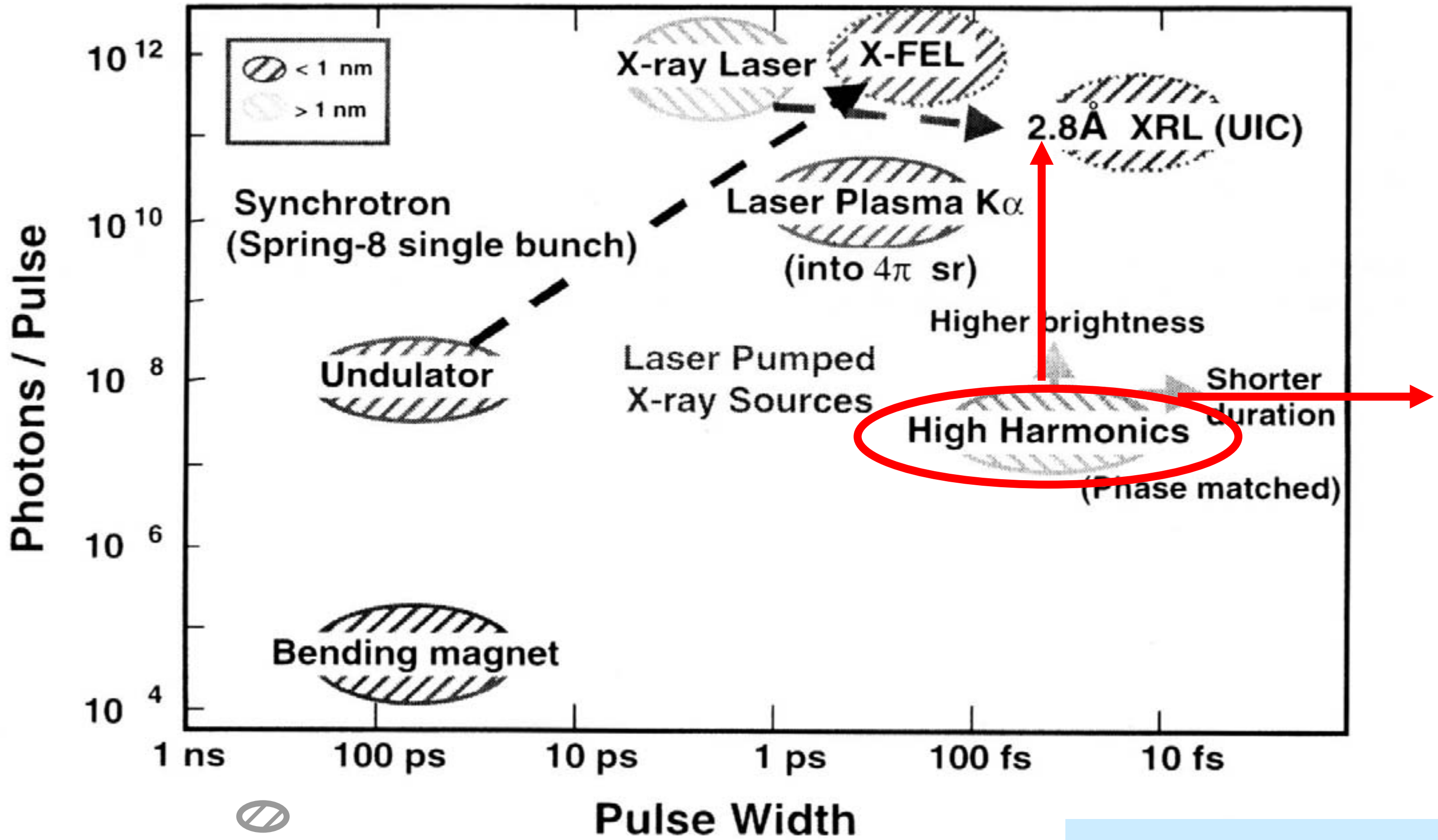


Fig. 1 High brightness x-ray sources

VUV	200 — 0.2nm
XUV	100 — 0.2nm
X-ray	30 — 0.01nm
soft-X-ray	30 — 0.2nm
hard-X-ray	0.2 — 0.01nm

- Prof. Y. Kato, in X-ray Lasers 2000

- Extremely short pulse high brightness coherent x-ray sources

High order harmonics

Conversion efficiency

Pulse duration

Intensity

- Phase matching
- Shaped driving field
- Powerful drivers
- ???

Enhancement and broadening of high harmonic supercontinuum

Outline

1. *Motivation*
2. *Harmonic generation in a shaped laser field by using a few cycle laser driver*
3. *Table-top fusion of cluster target driven by subpetawatt laser pulses*
4. *Conclusions*

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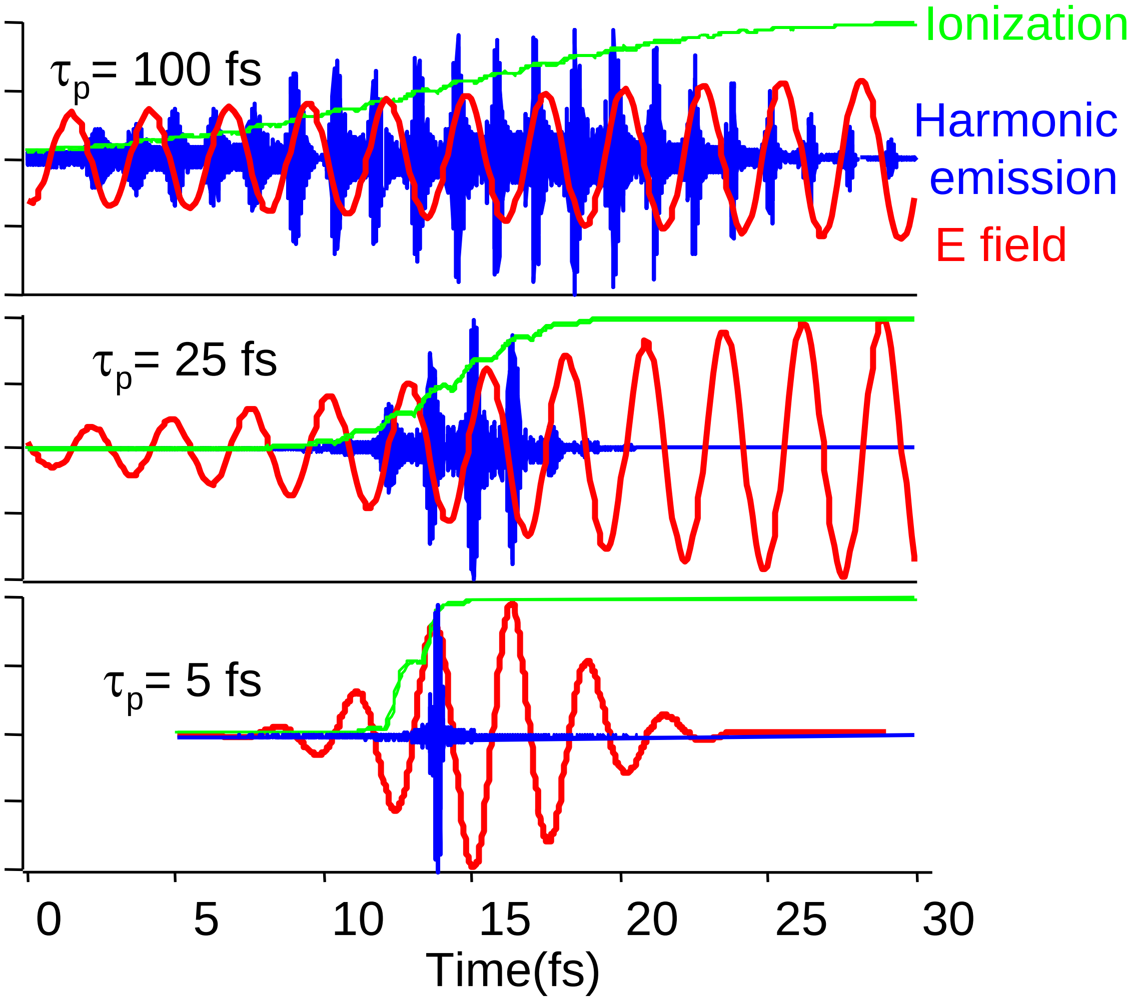
Generation of isolated single attosecond radiation usually requires a less than two cycles driving pulse

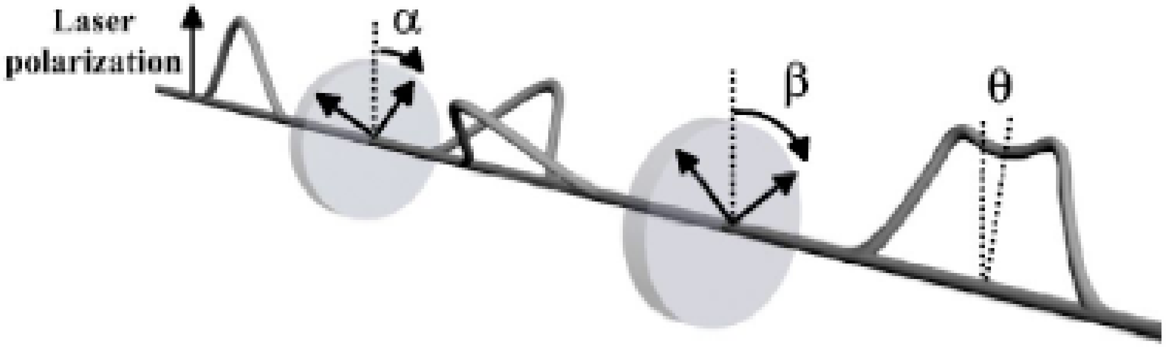


- ✓ 7fs, M. Hentschel et al., Nature, 414, 509 (2001)
- ✓ 5fs (CEP), A. Baltuska et al., Nature, 421, 611 (2003)

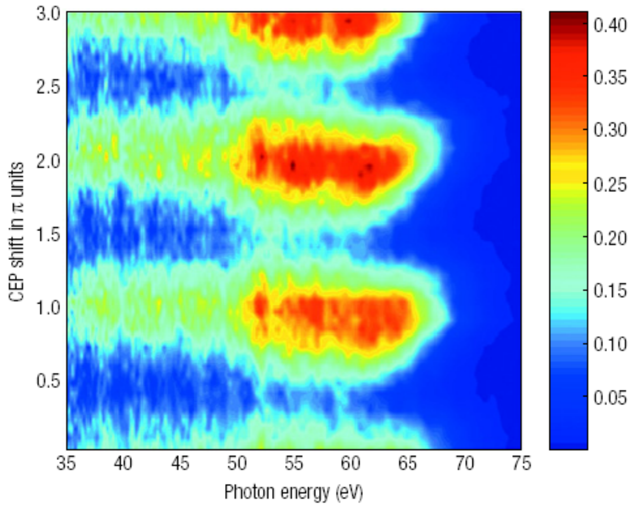
- ✖ Pulse duration limited by driving pulse duration
- ✖ Intensity limited by the few cycle pulse

I. P. Christov, M. M. Murnane, and H. C. Kapteyn, PRL 78, 1251 (1997)

Polarization-controlled time gating scheme for generating isolated attosecond pulse



$\tau_g = \varepsilon_{thr}\, \tau^2/(\ln(2)\delta\cos(2\beta))$

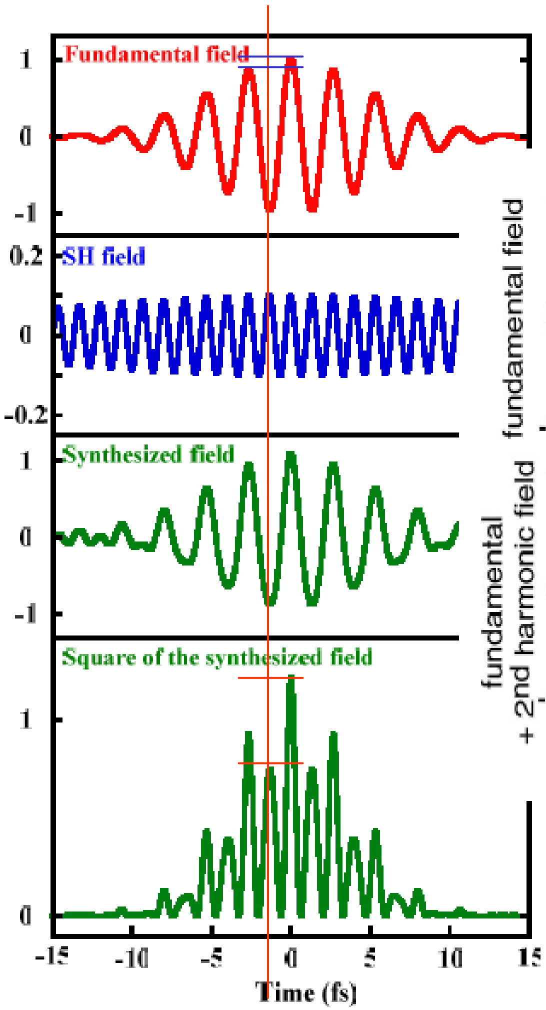


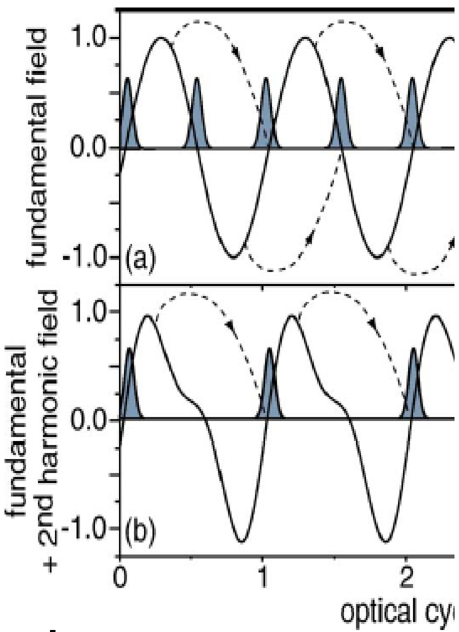
(with $\tau = 5$ fs, $\delta = 6.2$ fs, $\beta = 0°$)

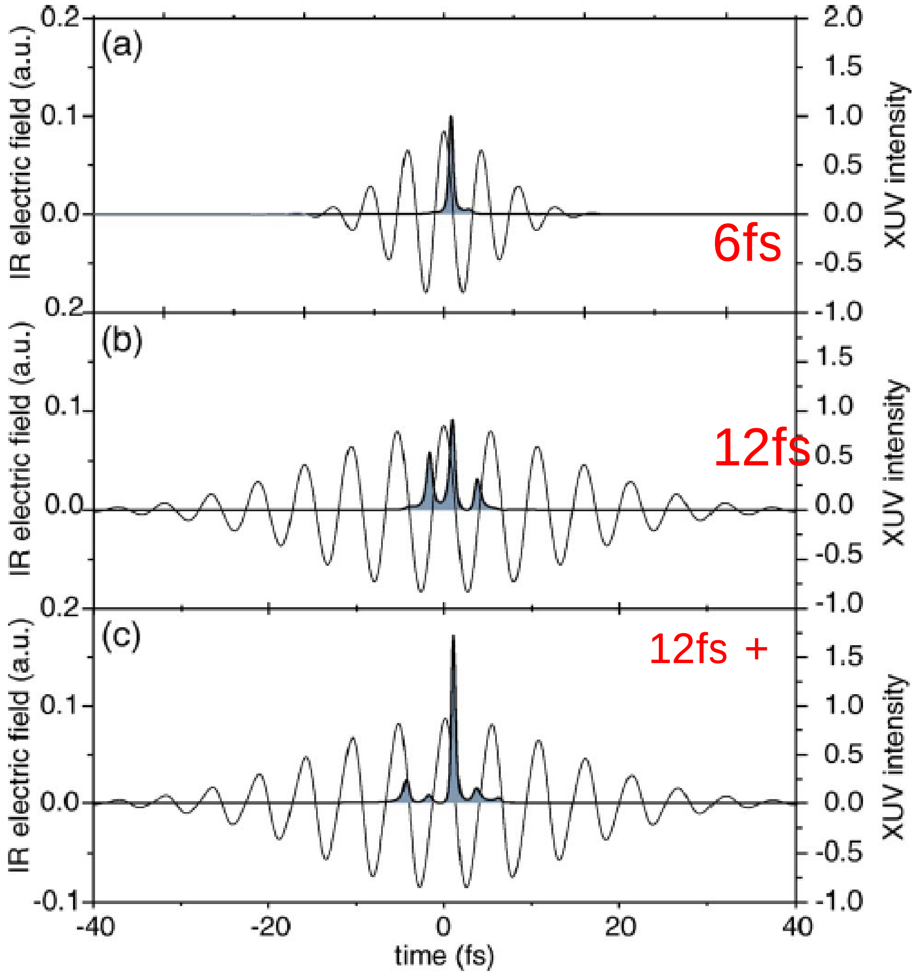
I.J. Sola, Nature Physics, 2, 319, (2006)
G. Sansone, Science 314, 443(2006)

The laser intensity in the effective narrow window is however reduced.

Two color scheme for generating isolated attosecond pulse using longer pulses



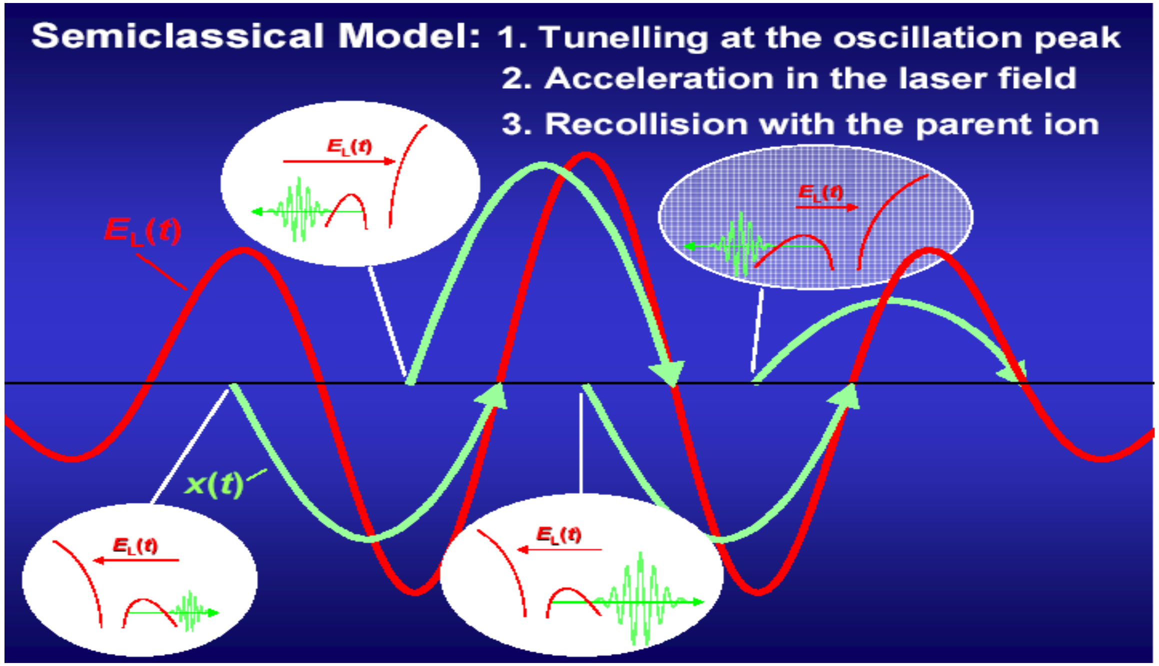


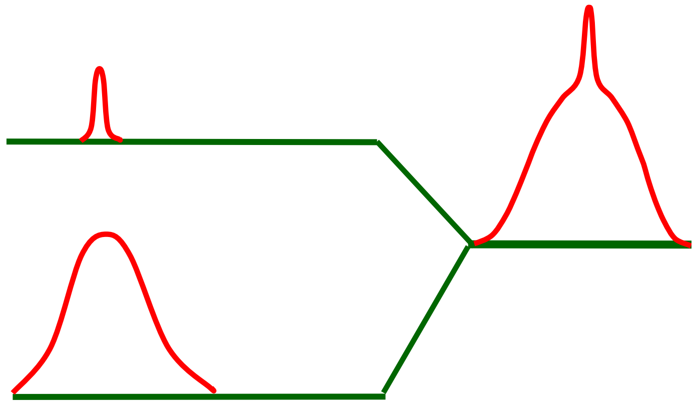


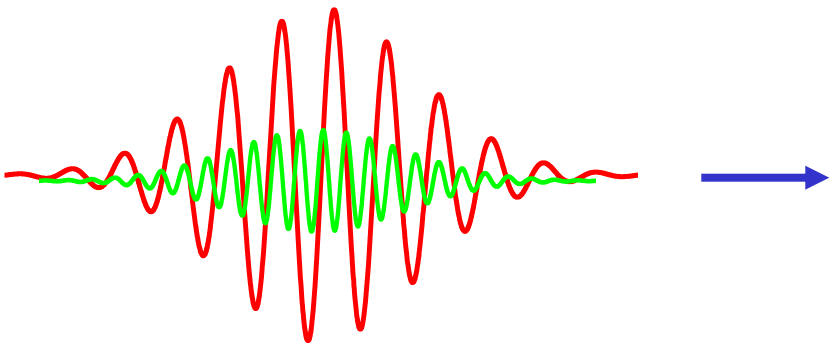
Yu Oishi et al.,
OE 14, 7230 (2006)

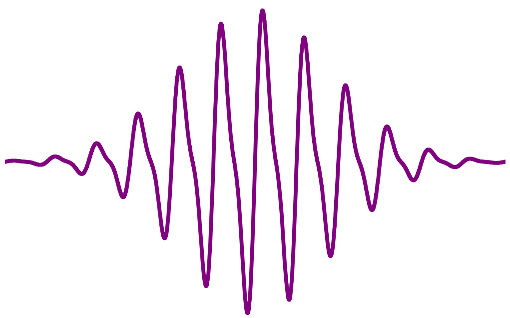
T.Pfeifer et al.,OL 31, 976 (2006)

Electron trajectory control in a shaped laser field

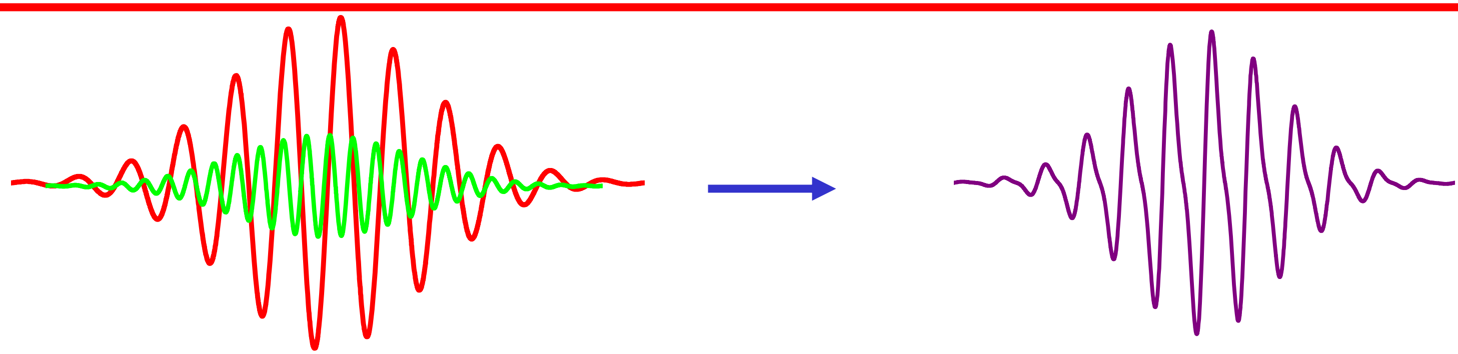


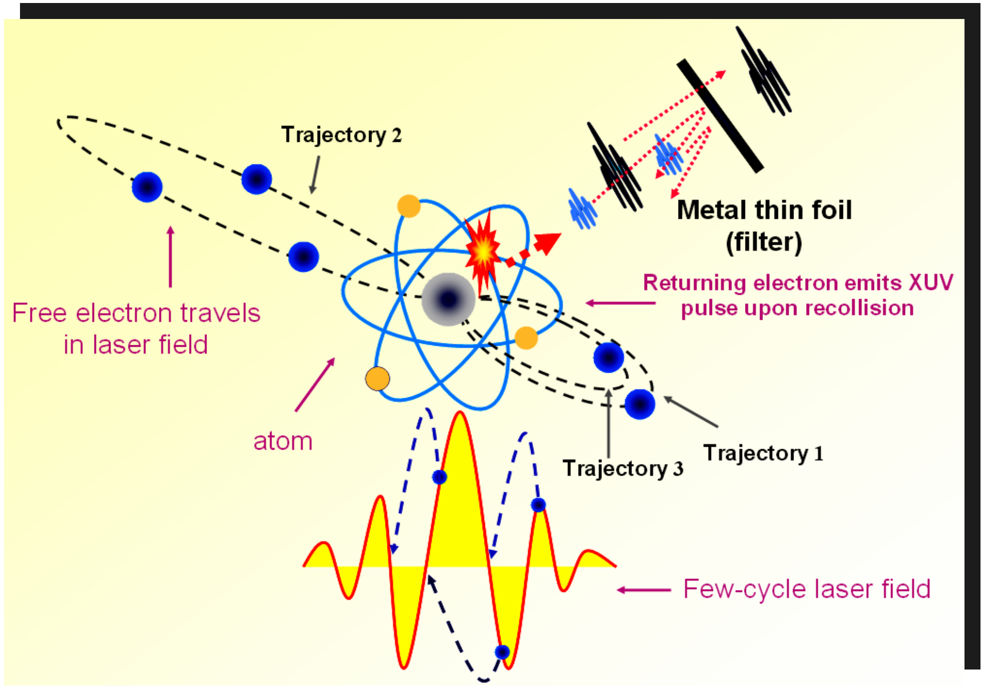




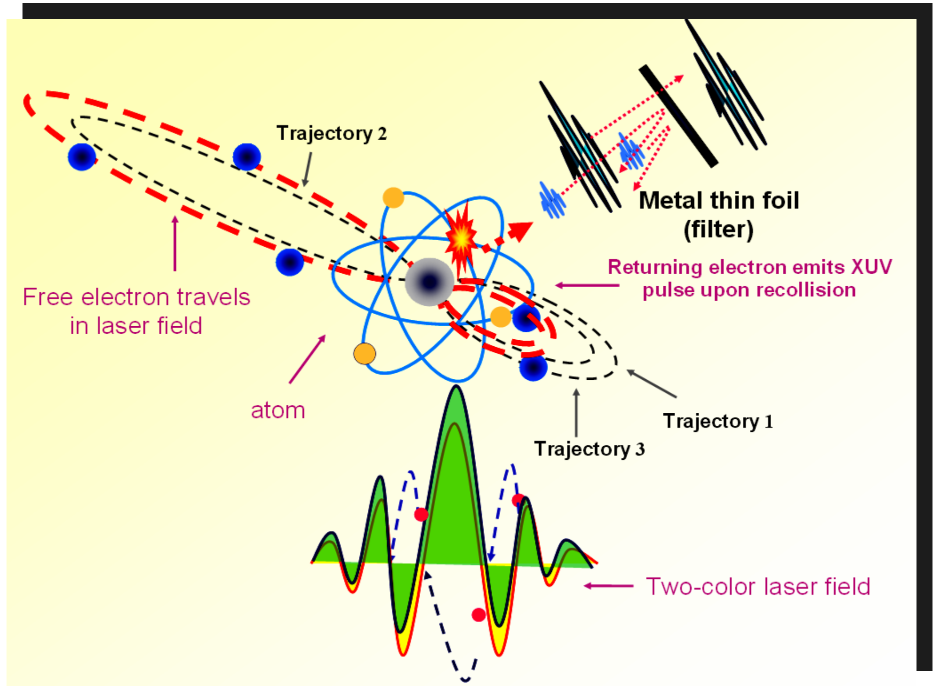


Electron trajectory control and <100as production in two color synthesized field with optimized delay





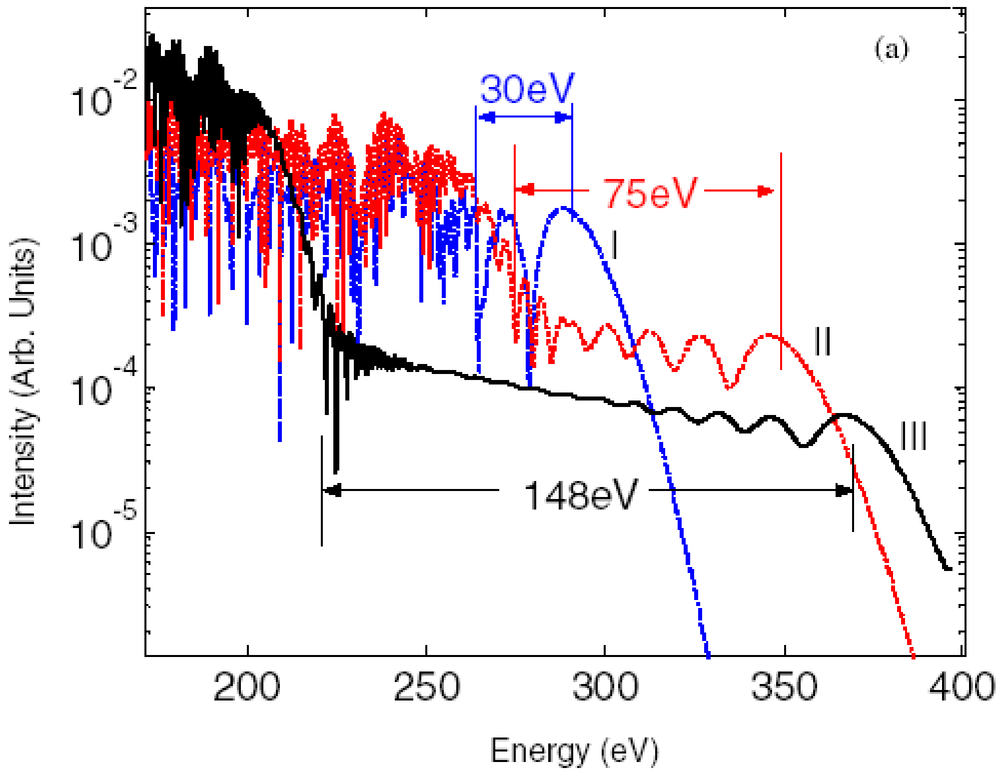
Single color field

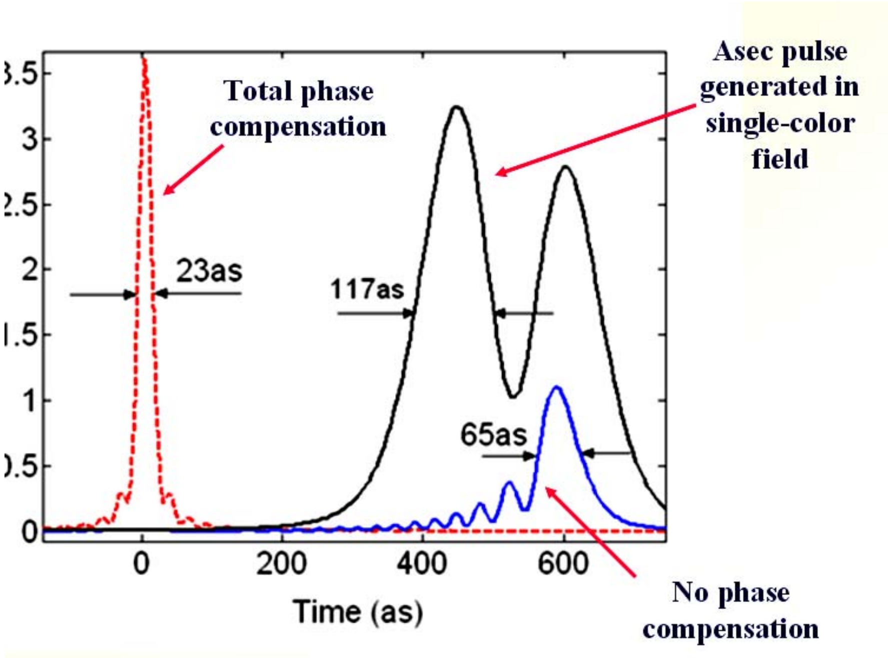


Two color field

Z. Zeng, Y. Cheng, X. Song, R. Li & Z. Xu, Phys. Rev. Lett. 98, 203901 (2007)

Two color synthesized field with optimized delay for producing <100as pulses

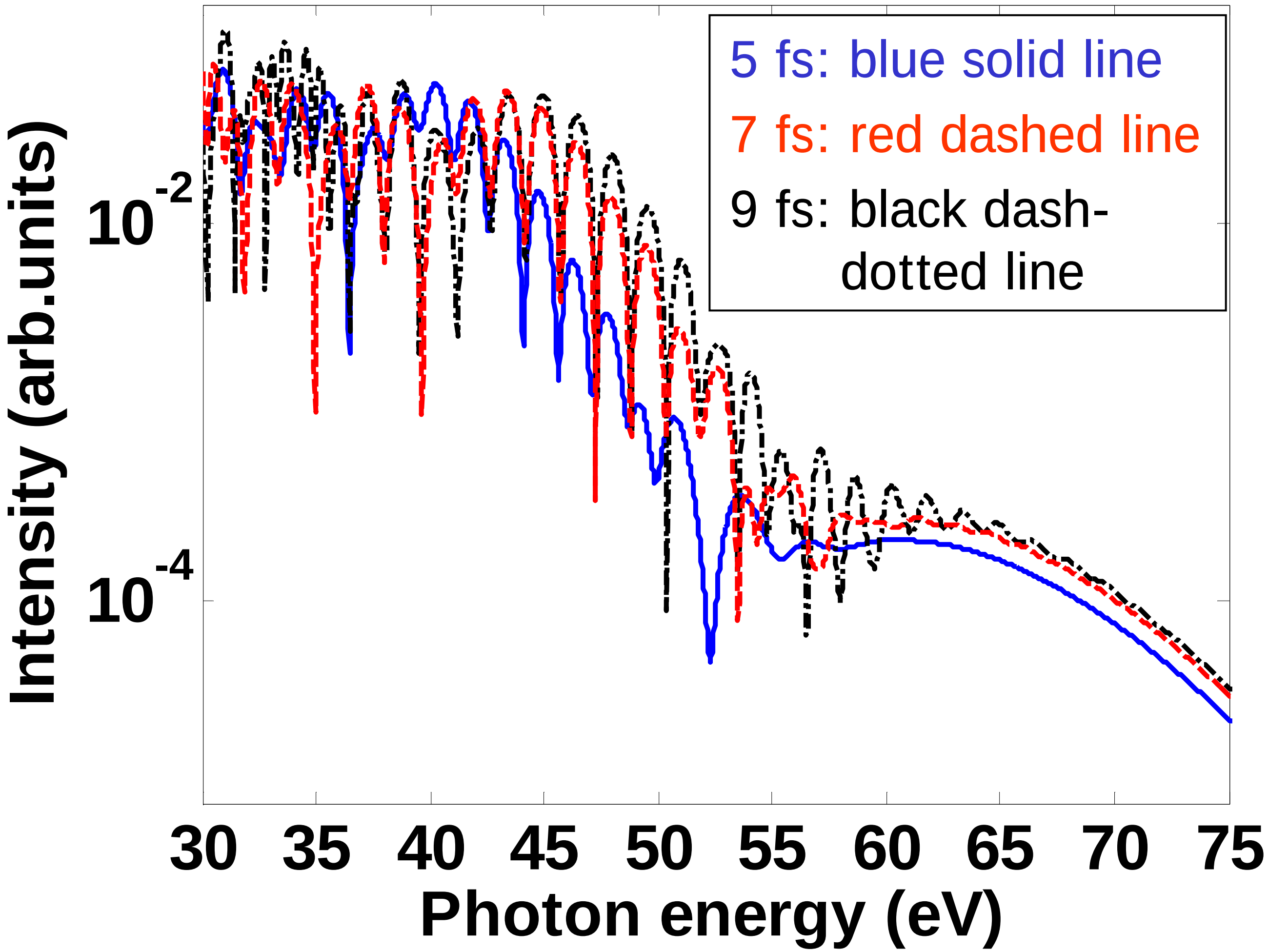


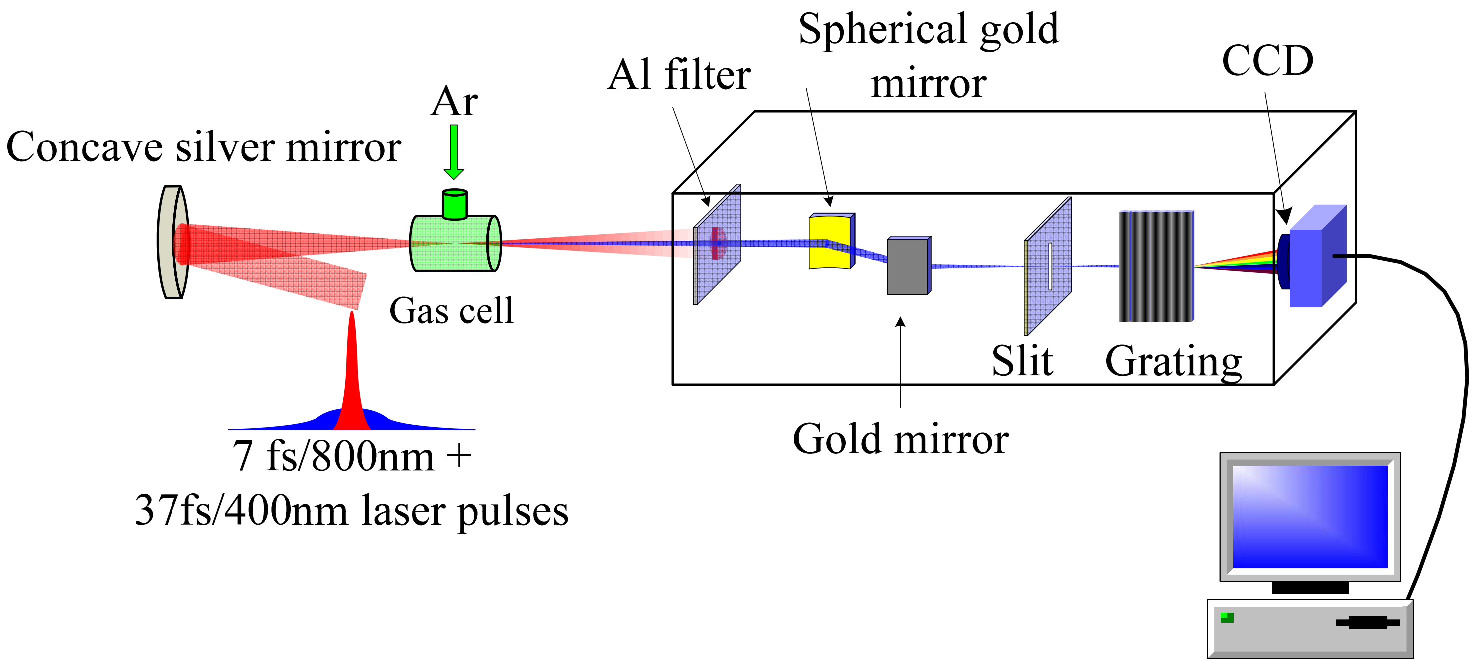


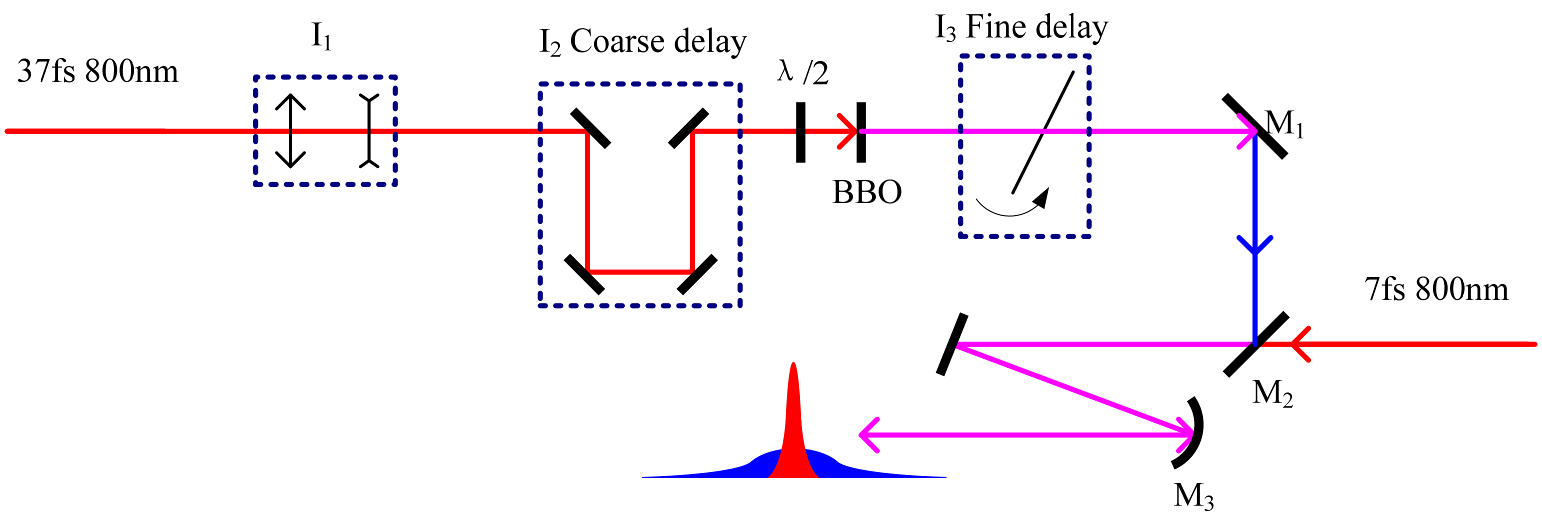
800nm 6fs + 400nm 21fs

Z. Zeng, Y. Cheng, X. Song, R. Li & Z. Xu, Phys. Rev. Lett. 98, 203901 (2007)

Calculated two-color field driven harmonic spectra with the 800nm few cycle laser pulses of different durations. The time delay between the two color pulses is T/16.

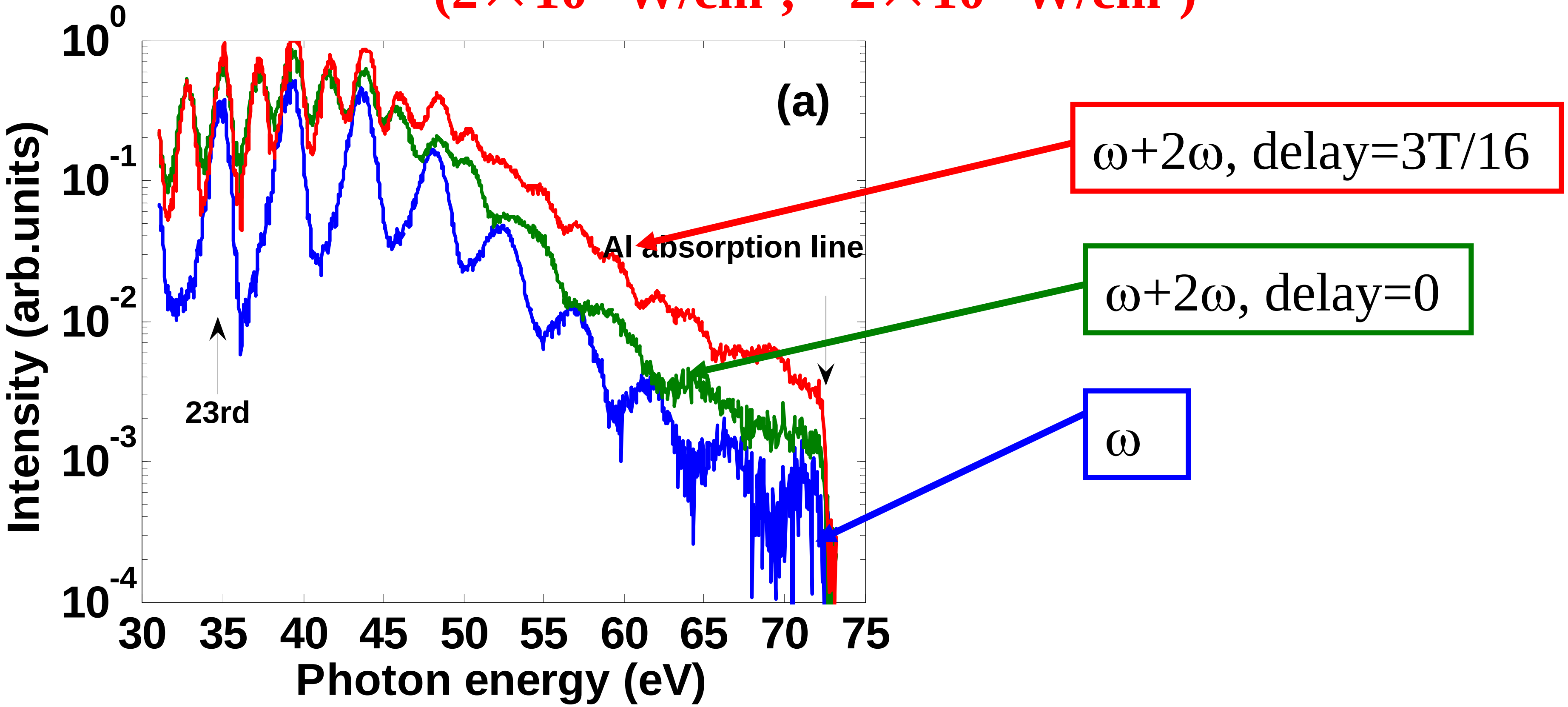



Concave silver mirror
Ar
Gas cell
7 fs/800nm +
37fs/400nm laser pulses
Al filter
Spherical gold
mirror
CCD
Slit
Grating
Gold mirror


37fs 800nm
I_1
I_2 Coarse delay
λ /2
BBO
I_3 Fine delay
M_1
7fs 800nm
M_2
M_3

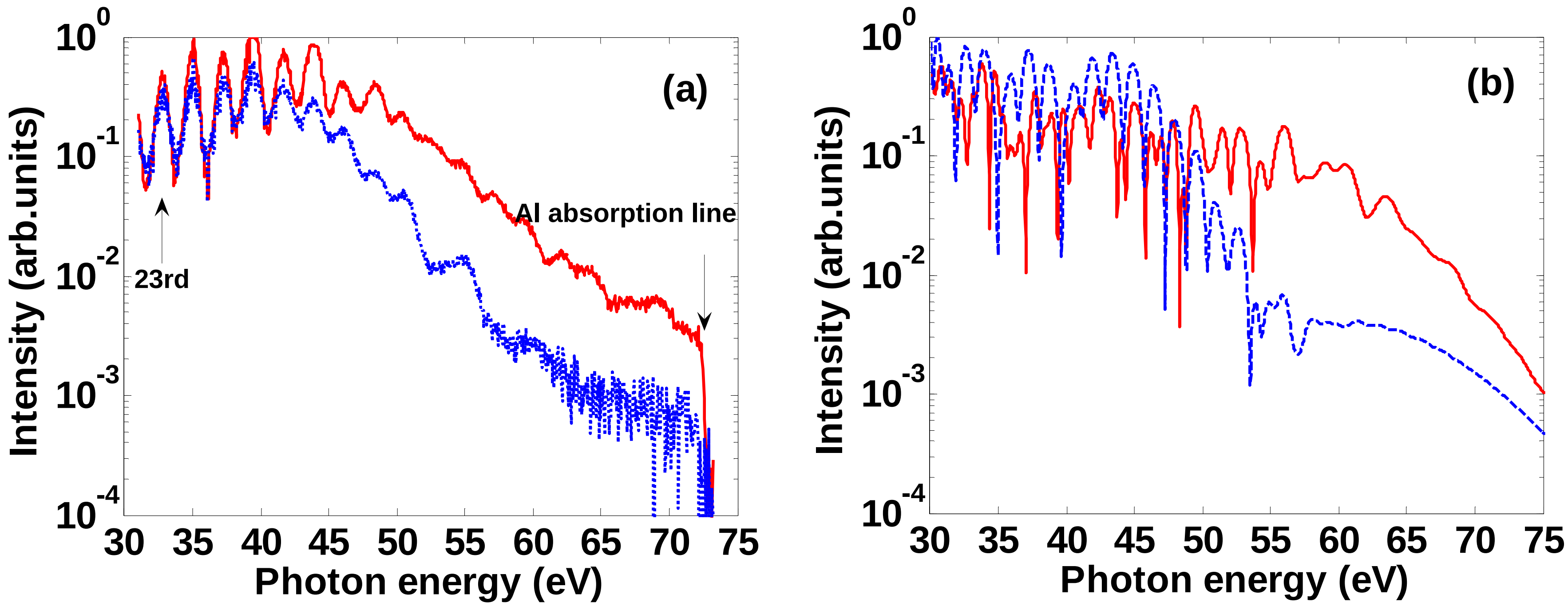
Enhancement and broadening of XUV supercontinuum in Argon

7fs/800nm + 37fs/400nm
(2×10^{14}W/cm^2, 2×10^{13}W/cm^2)



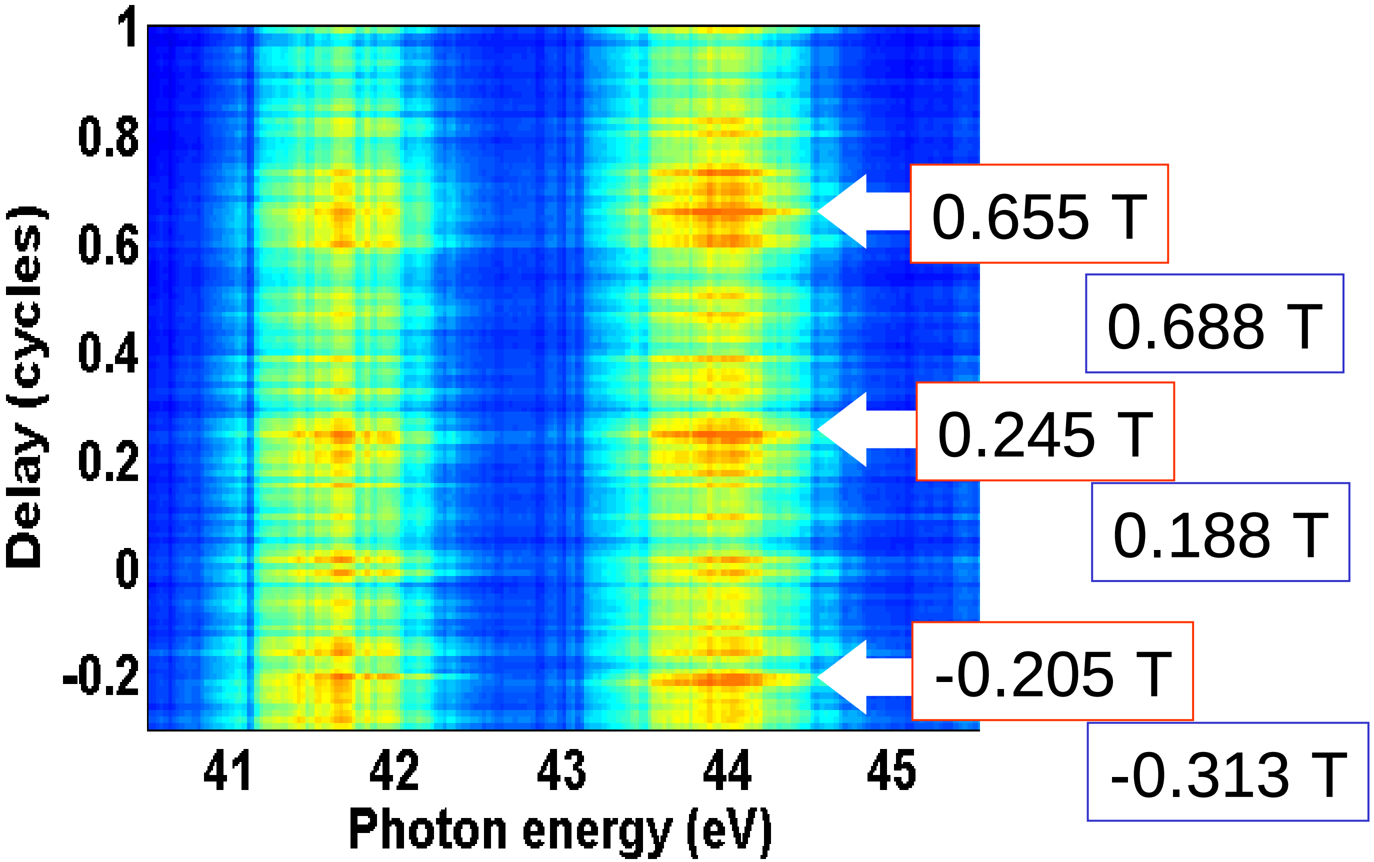
Opt. Lett. 33, 234(2008)

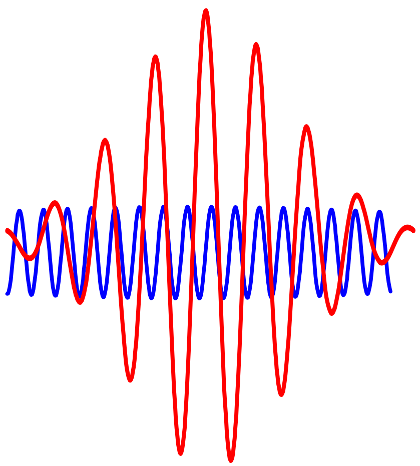
Experimental (a) and calculated (b) HHG obtained with different time delays



- T/16 (blue dashed curve)
- 3T/16 (red solid curve)

The experimental two color field driven harmonic spectra as a function of relative delay

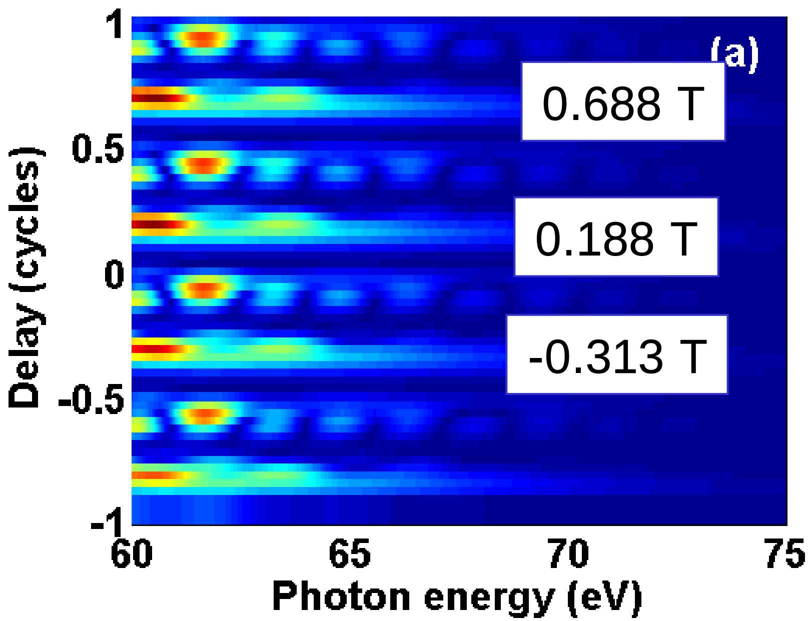




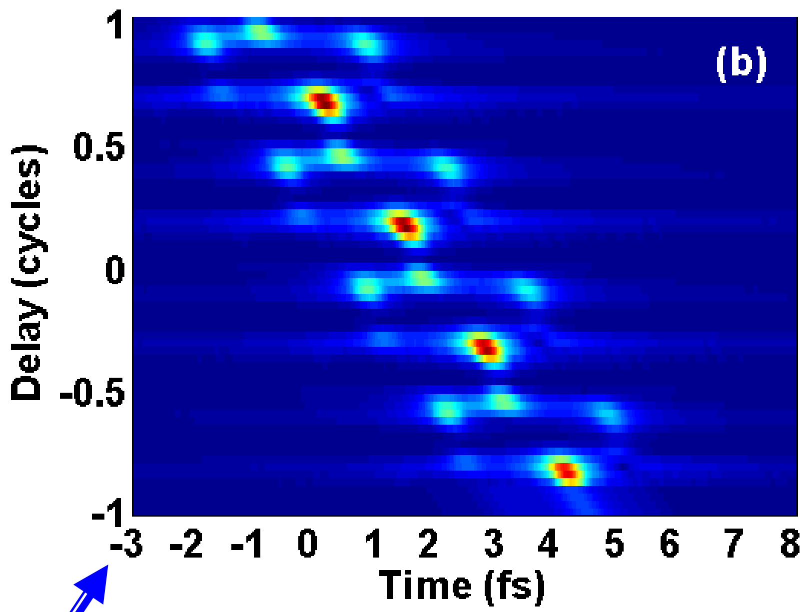
The uncertainty of the time delay calibration is better than 35%, the relative timing uncertainty is 18%.

The calculated two color field driven harmonic features at the cutoff region

- Frequency domain



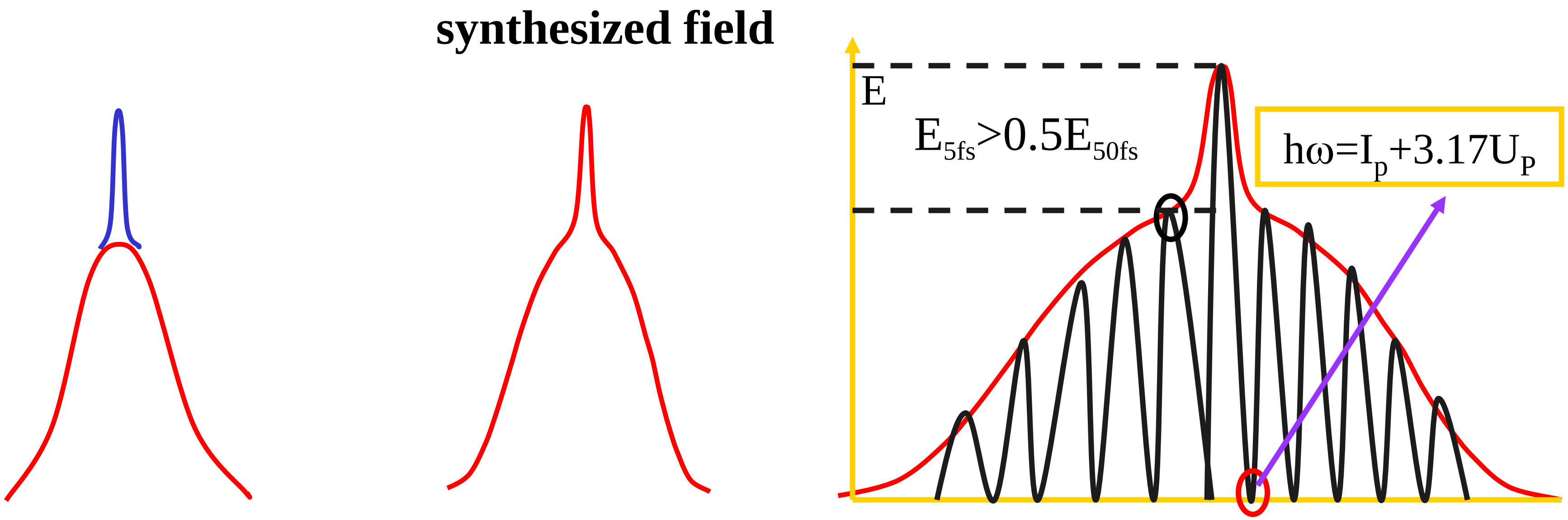
- Time domain



Isolated attosecond pulse with variable duration and intensity

Opt. Lett. 33, 234(2008)

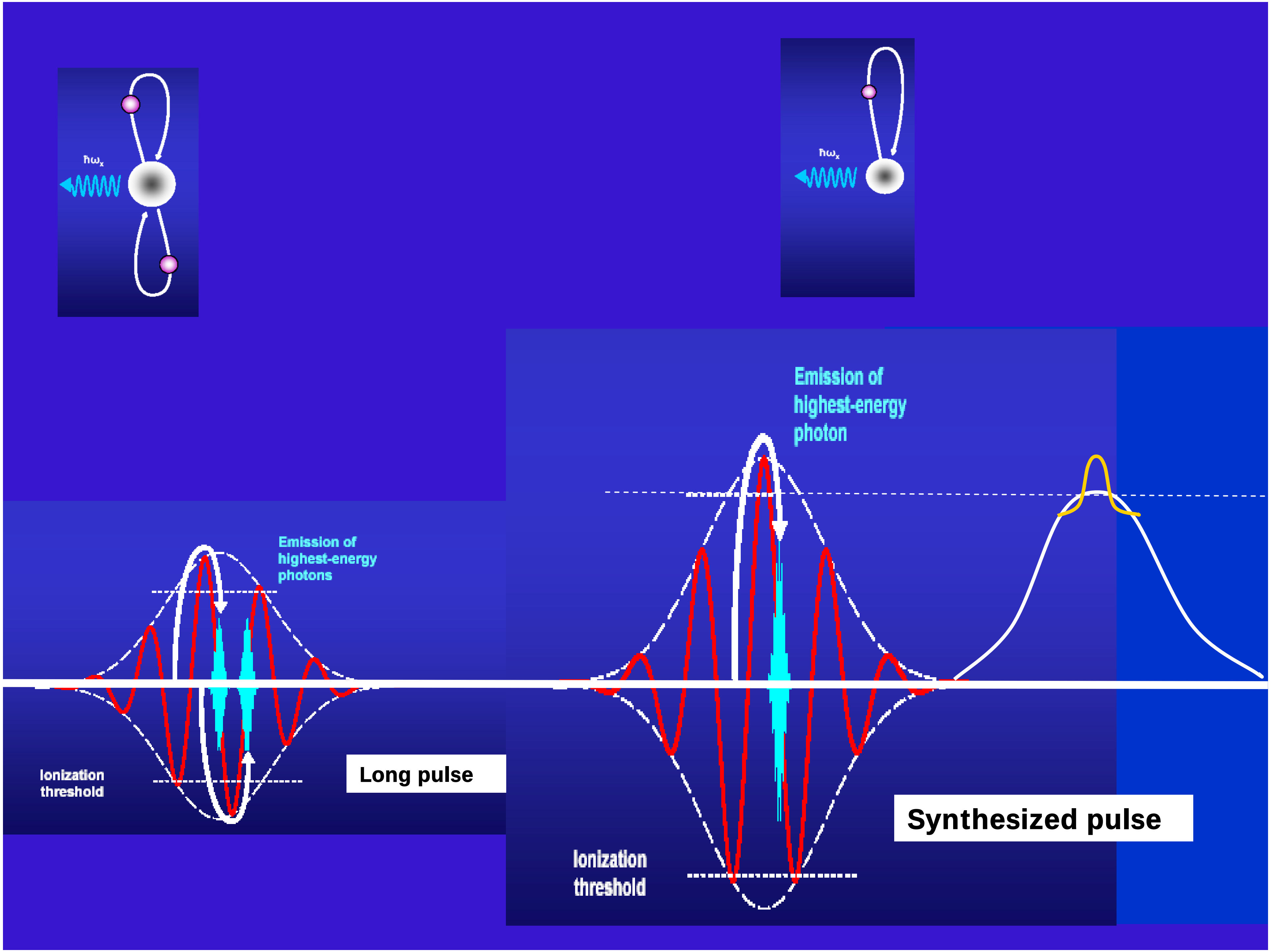
Temporal Confinement of High Harmonic Emission with an Intense Synthesized Laser Field



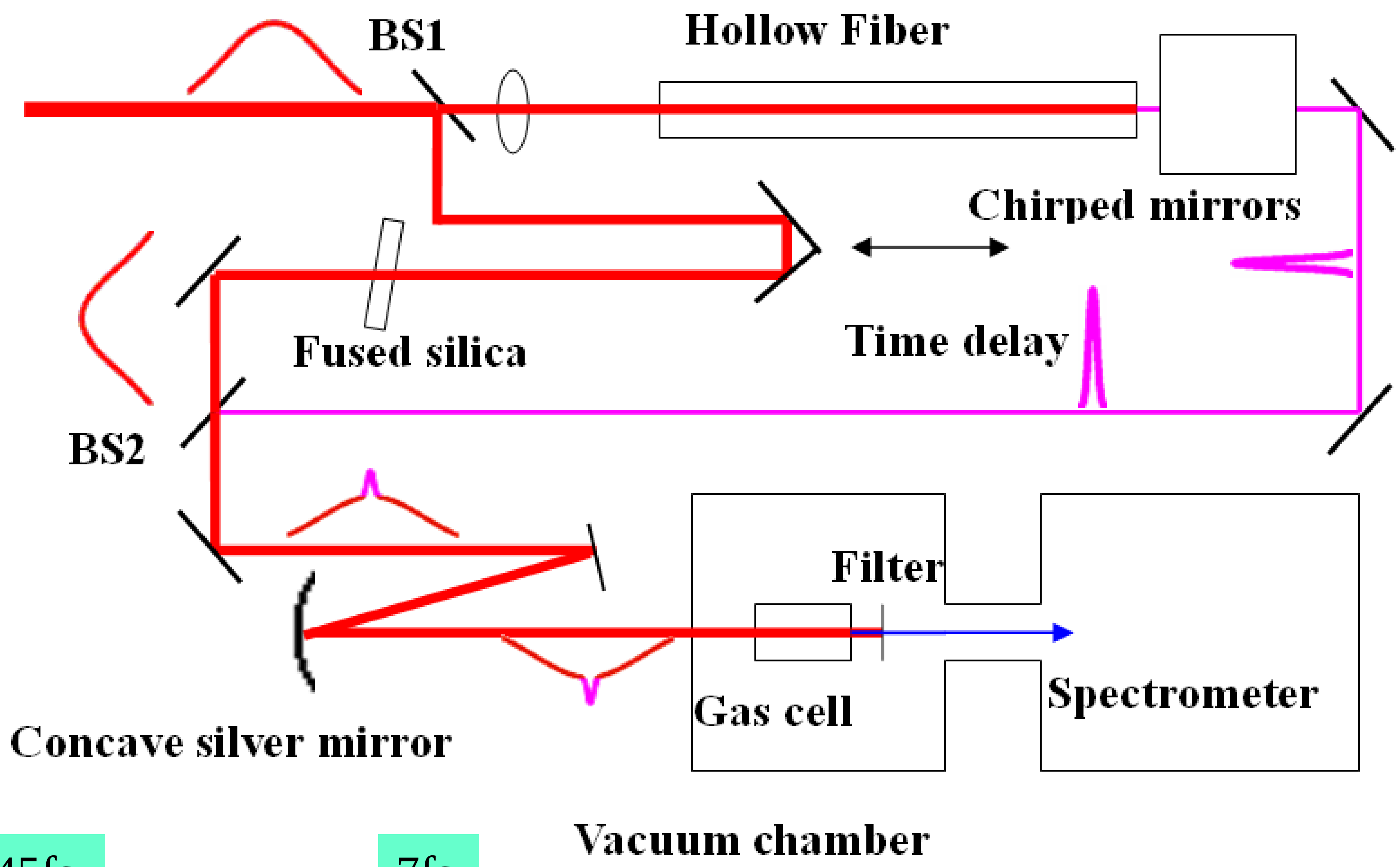
5fs pulse: 8.8×10^{13}W/cm^2,

50fs pulse: 3.5×10^{14}W/cm^2

ISUILS 2, Quebec, Canada, 2003
Physical Review A70, 053810(2004)


ħωx
ħωx
Emission of highest-energy photons
Ionization threshold
Long pulse
Emission of highest-energy photon
Ionization threshold
Synthesized pulse

Experimental Setup



45fs

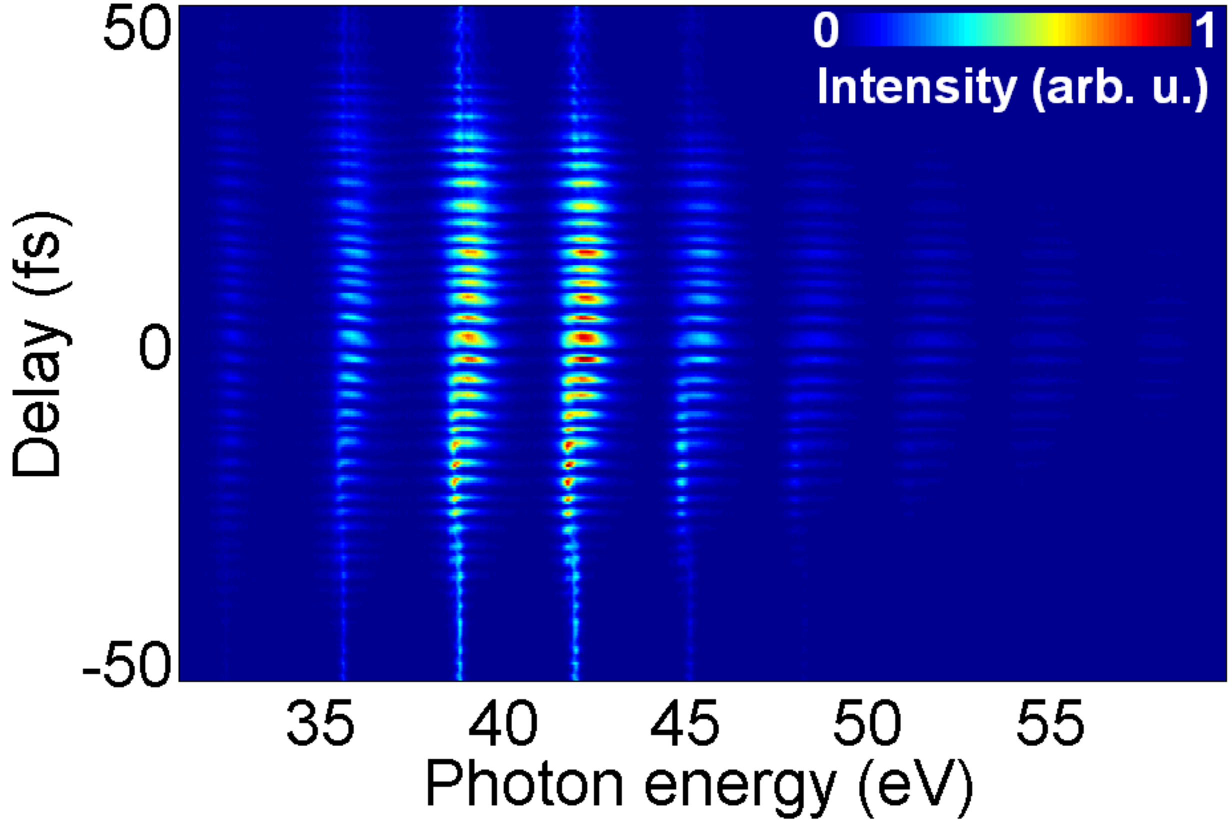
1.7×10^{14} W/cm^2

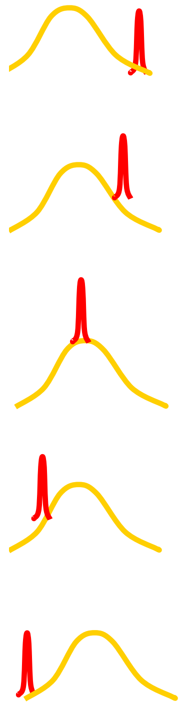
7fs

3.4×10^{13} W/cm^2

H. Xiong et al.,
PRA **75**, 051802(R)(2007)

HHG as a function of the delay between two pulses



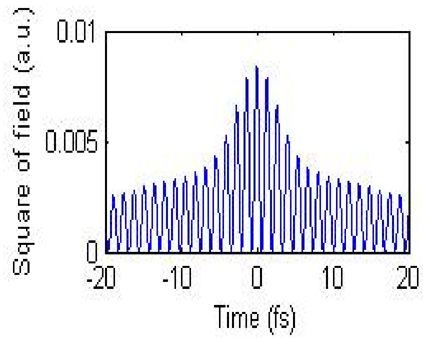


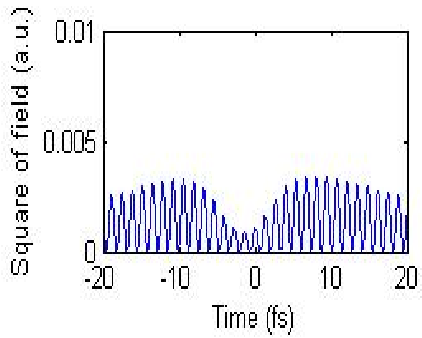
45fs

1.7×10^{14} W/cm^2

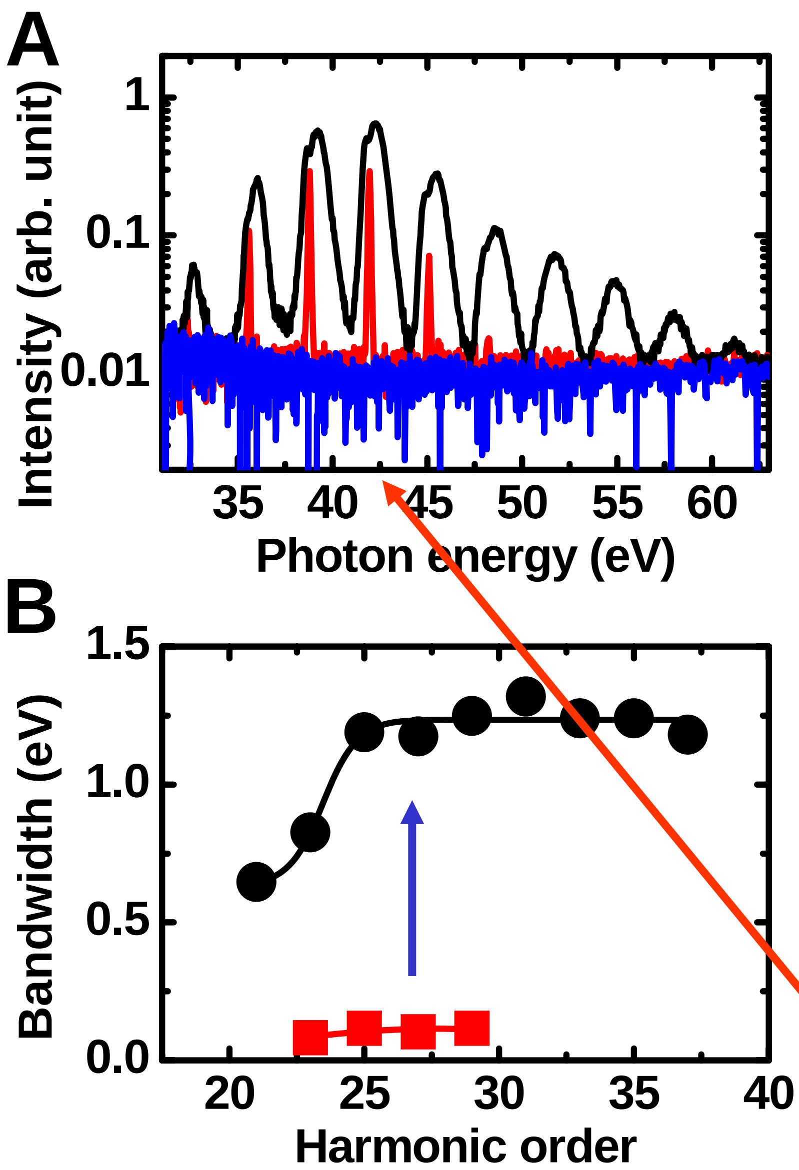
7fs

3.4×10^{13} W/cm^2

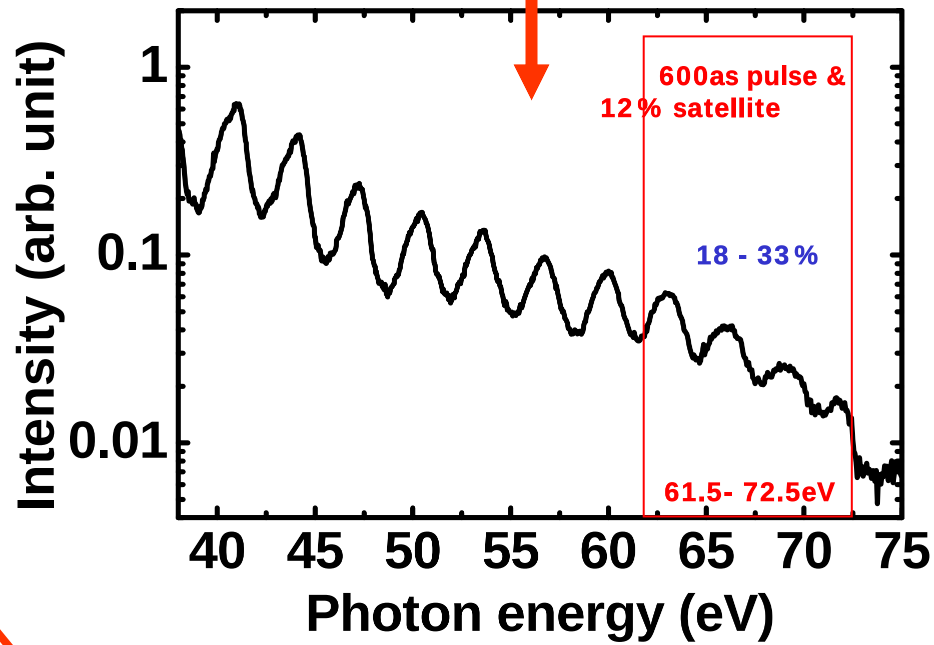




Temporal Confinement of Harmonic Emission towards a single strong attosecond pulse

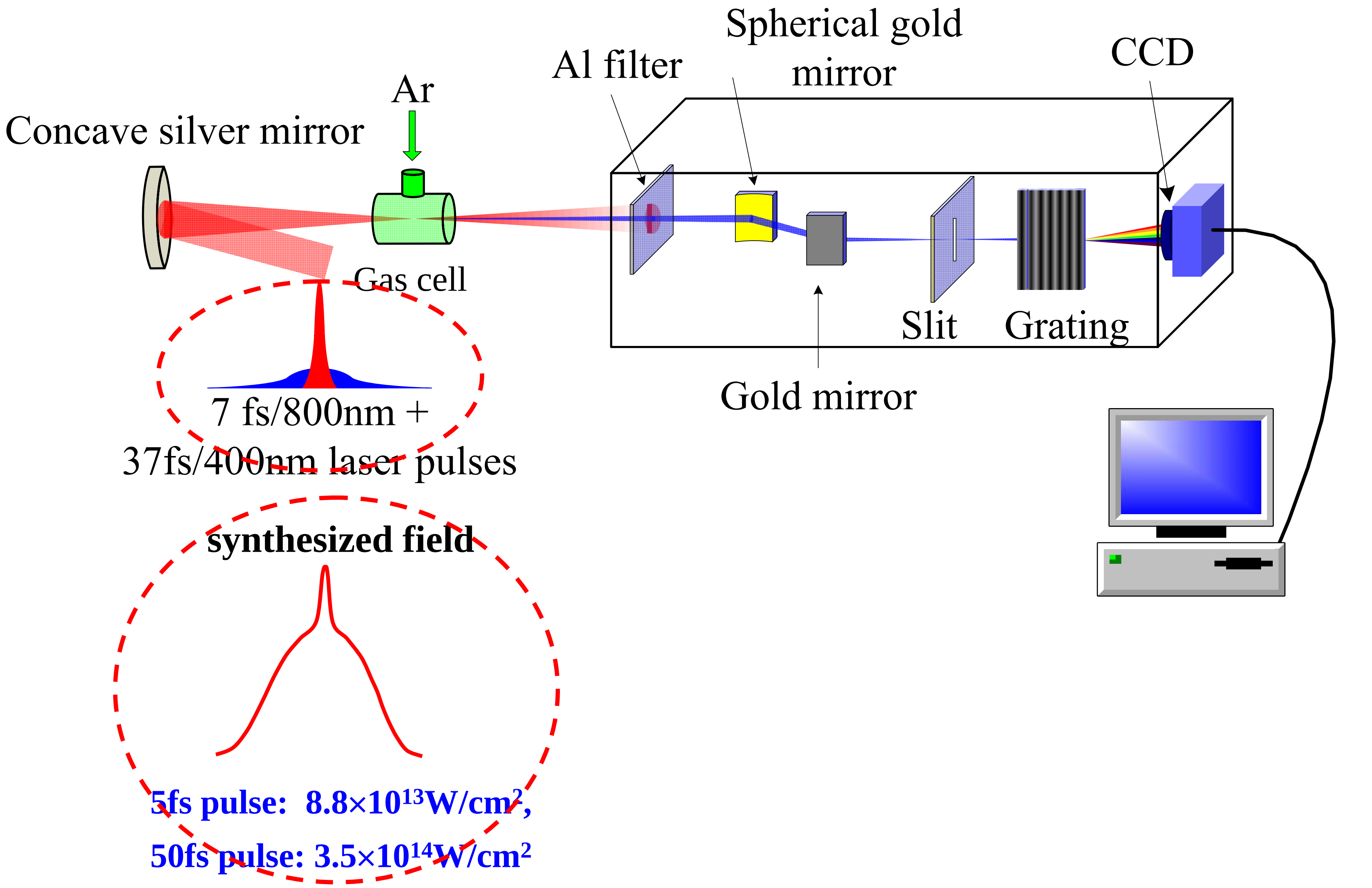


1.7×10^14 W/cm²	**5:1**	3.4×10^13 W/cm²
45fs		7fs
2.4×10^14 W/cm²	**4:1**	5.9×10^13 W/cm²



The 27th harmonic signal is increased by 17 times, while there is only a 5.5% increase in the energy of 7fs pulse.

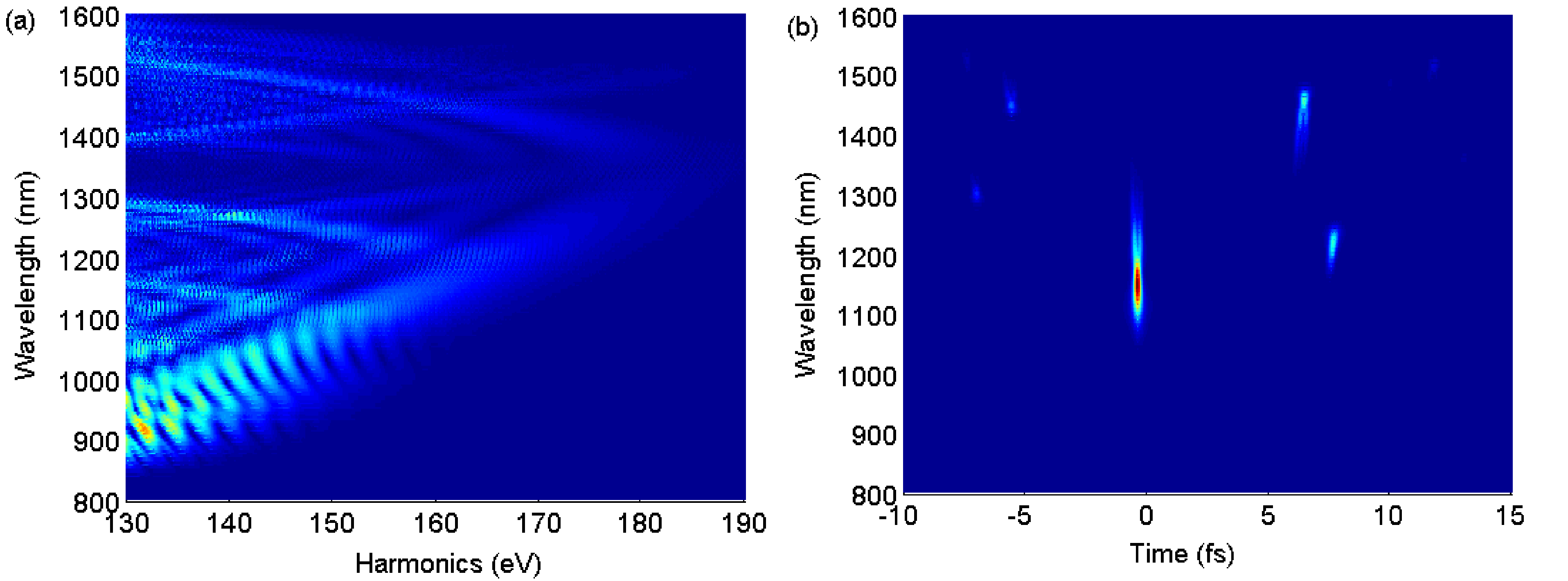
A few cycle pulse is always necessary in the previous schemes



Single 220as pulse driven by detuned two color field

(800nm/35fs + ?)

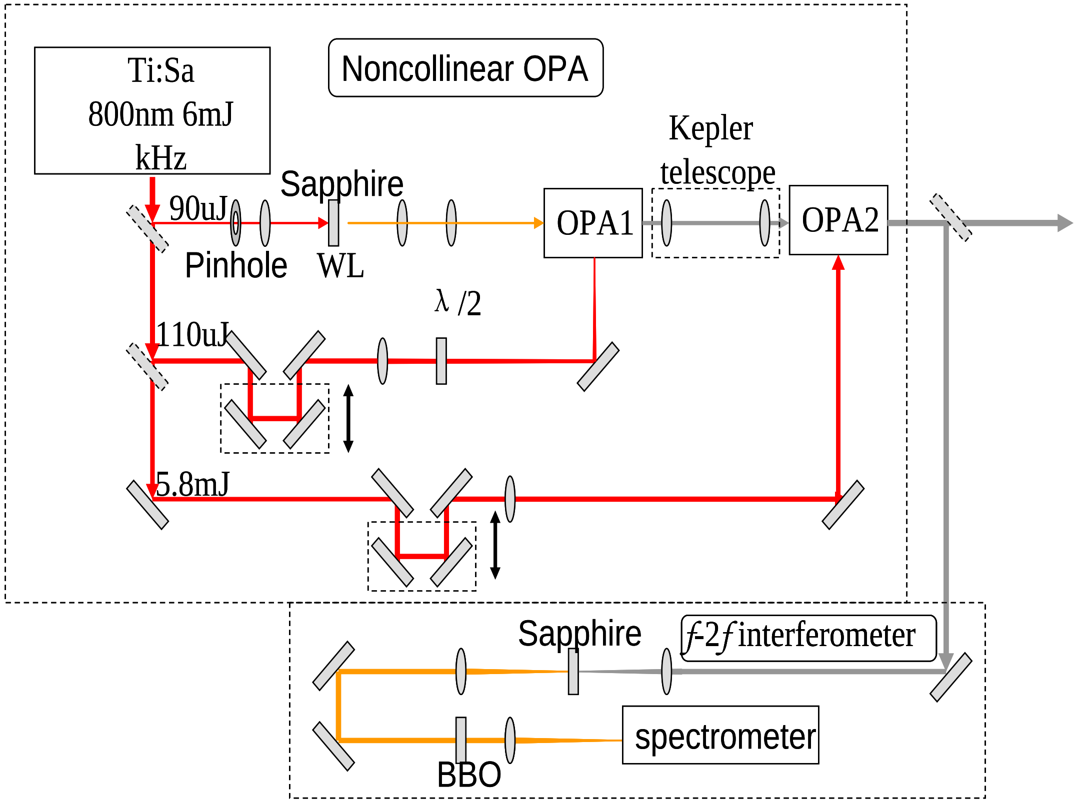
? = 800-1600nm

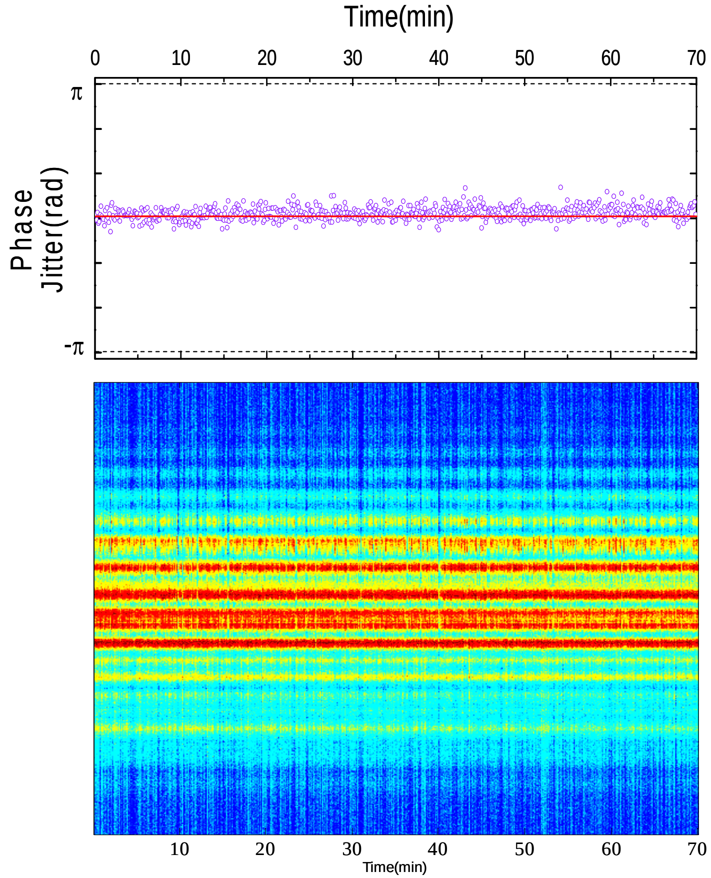


Previous work, ω+2 ω' Merdji et al., Opt. Lett. 32, 3134(2007)

This work, ω1+ω2 Zeng et al., J. Phys. B 41, 215601(2008)

CEP stablized IR laser





Signal：1.3 μ m- 2.3 μm.　Idler： 1.3 μ m- 2.3 μm

Conversion E：40％　　CEP Jitter RMS：0.1433rad

Outline

1. *Motivation*
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3. *Table-top fusion of cluster target driven by subpetawatt laser pulses*
4. *Conclusions*

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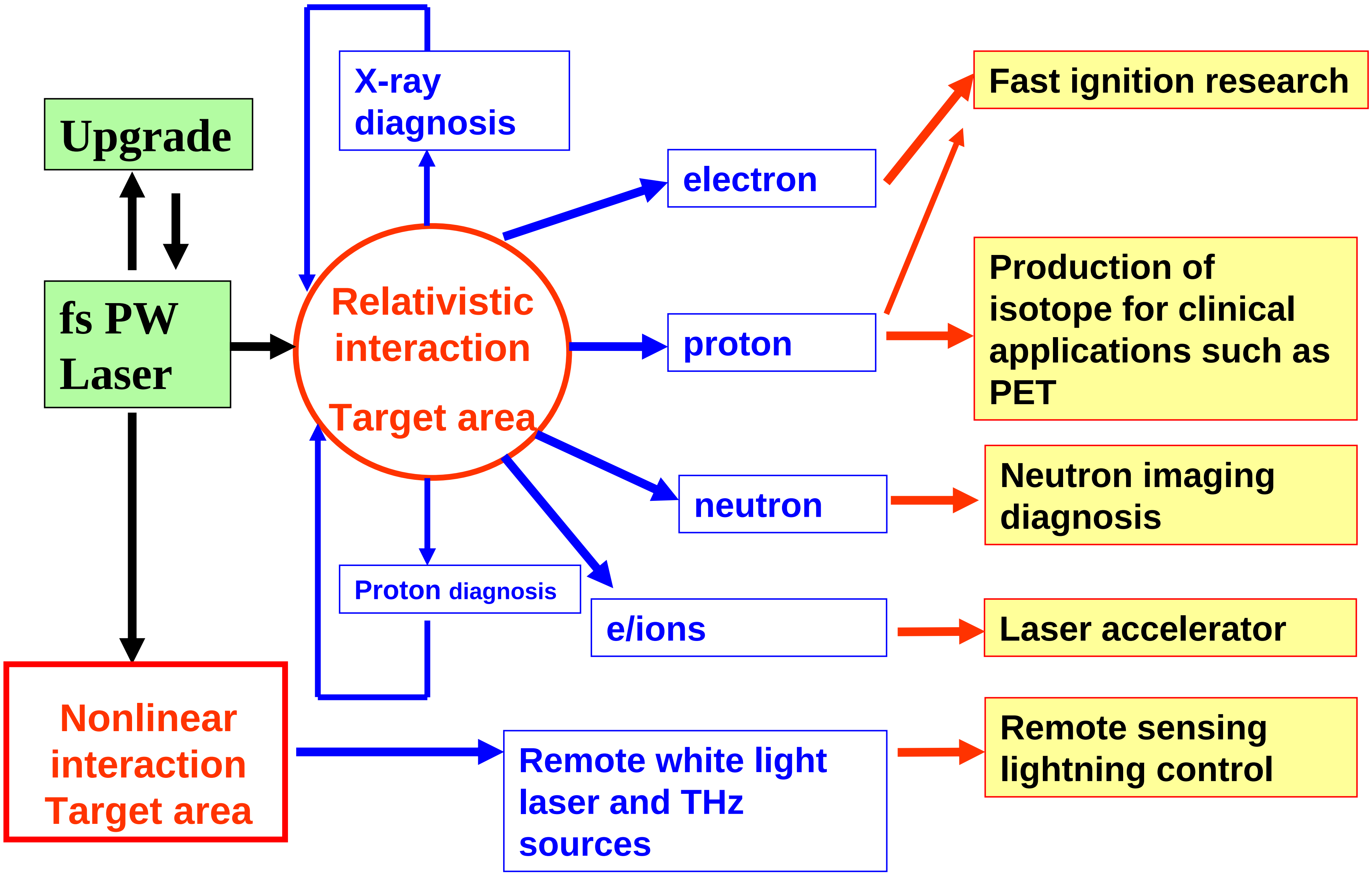
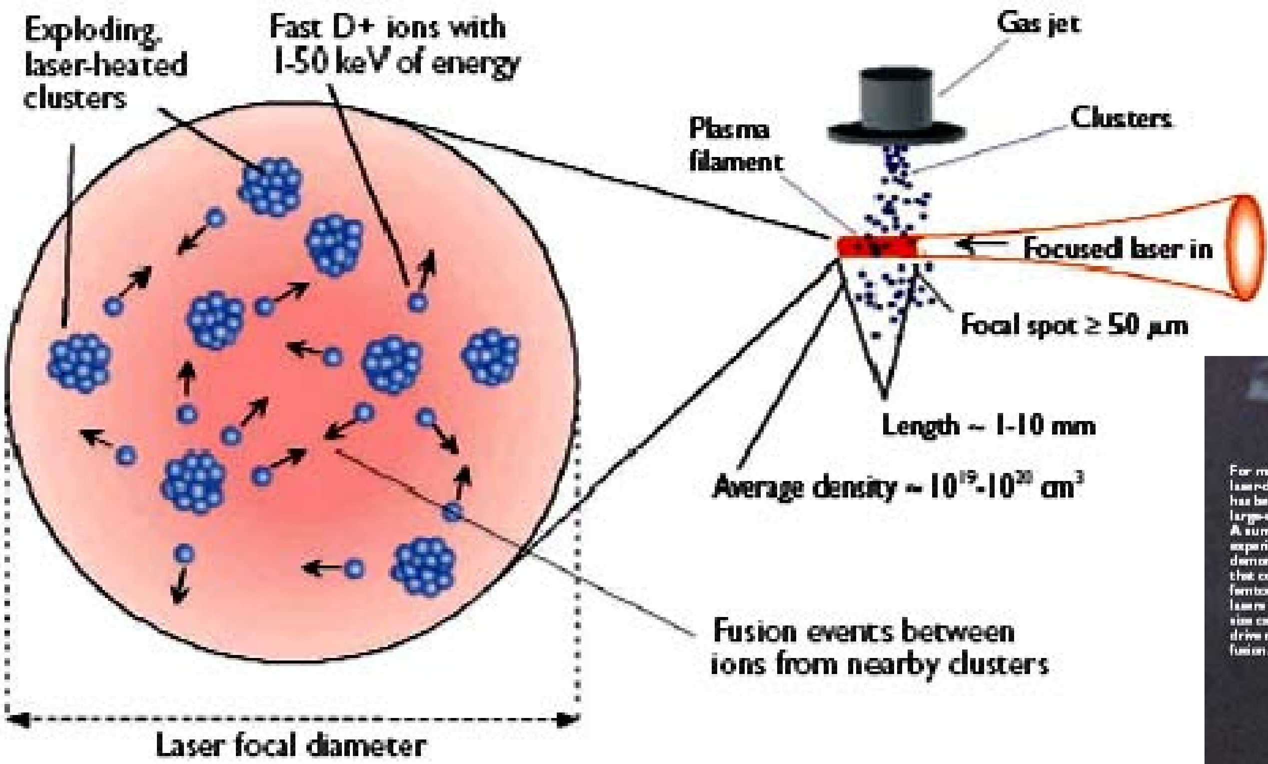
Fs PW laser experimental platform

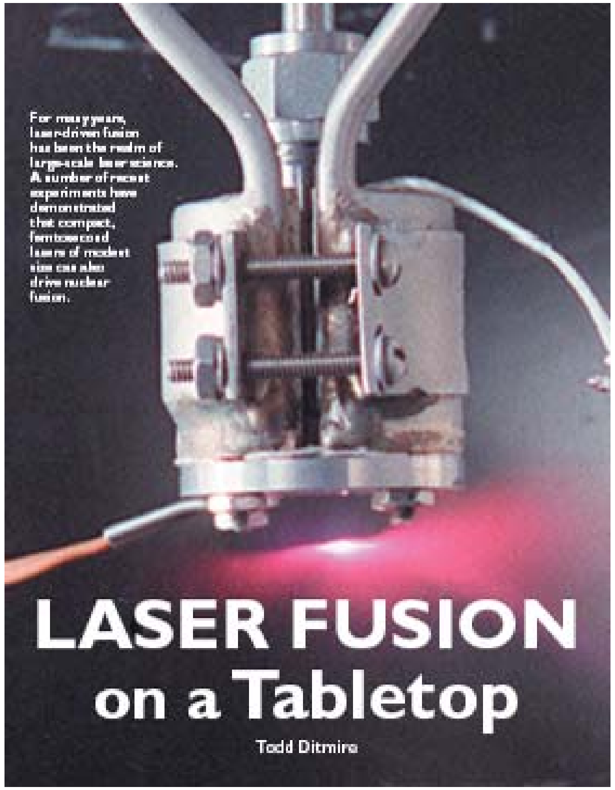


Short-pulse mono-energetic point-like source of fusion neutrons



T. Ditmire Nature 398, 489 (1999)

E=120mJ/pulse
τ=35fs, λ=800nm
I=2×10^{16}W/cm^2



- Compact laser driven nanoexplosion leads to fusion from clusters
- High-repetition-rate table-top laser fusion facility
- High-repetition-rate point-like source of neutrons of unique properties

Short-pulse mono-energetic point-like source of fusion neutrons

10^5 neutrons/1J laser energy

T. Ditmire, et al., Nature, **398**:489 (1999)

↓

Coulomb explosion time of D_2 clusters only 30fs

↓

>10^8 neutrons/shot possible with 30J/30fs PW laser

Dynamic of radiation damage

Key issues for enhancing the neutron yield

$$D + D \rightarrow He^3(0.82MeV) + n(2.45MeV)$$

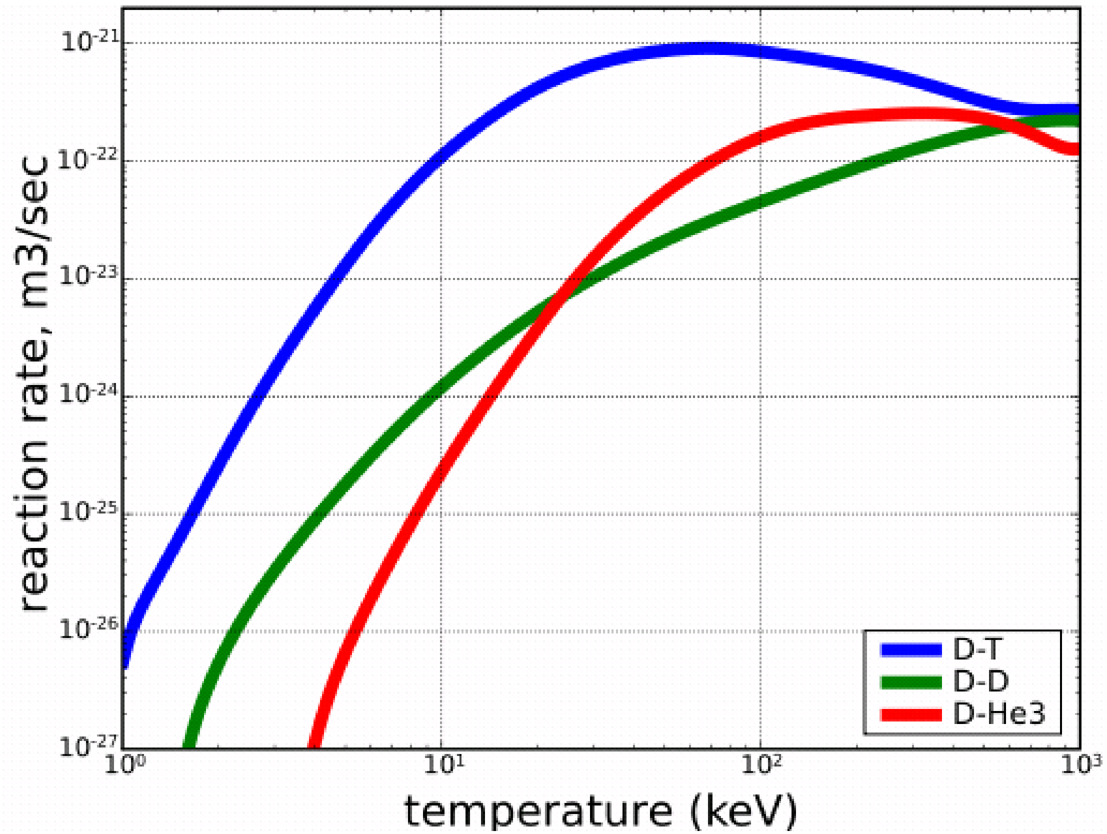
Inter cluster fusion

$$Y_{\mathrm{IC}} = \frac{1}{2}\bar{\rho}^2 L_{\mathrm{IC}} V_r \langle \sigma \rangle_{\mathrm{IC}}$$

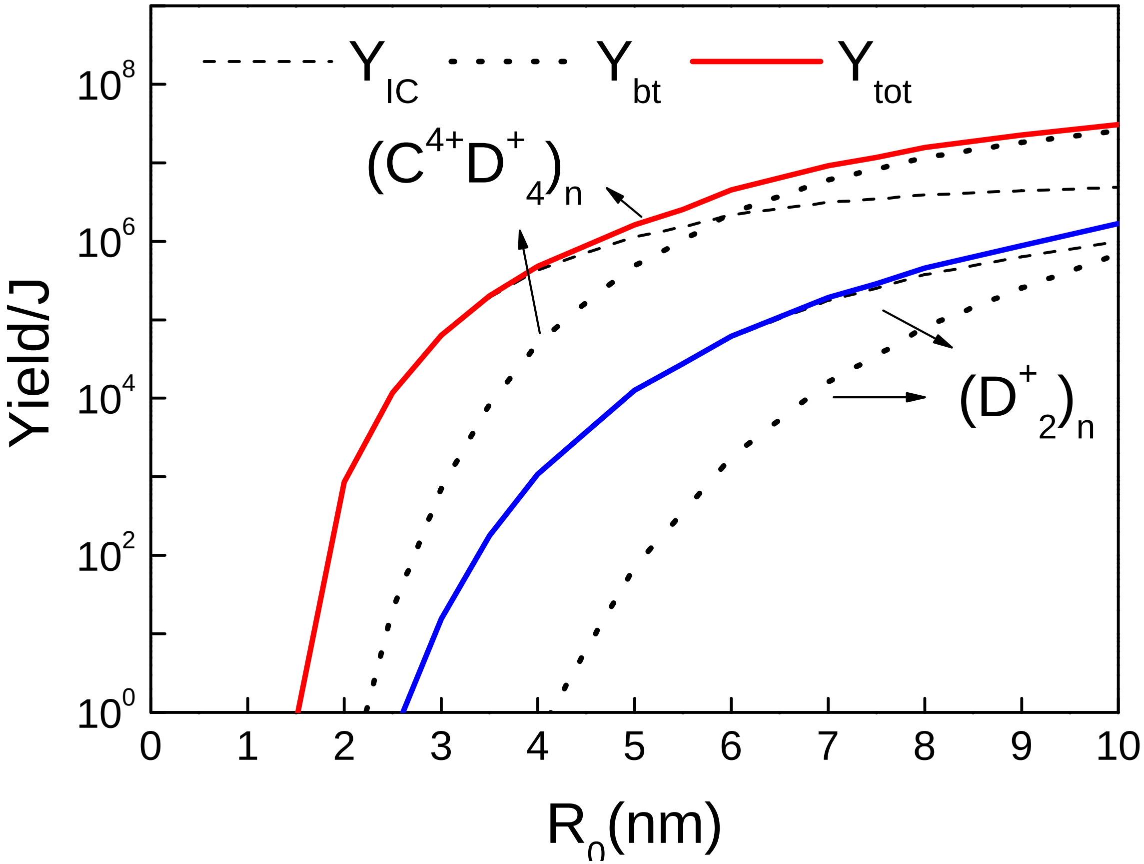
Beam target fusion

$$Y_{\mathrm{bt}} = \frac{1}{2}\bar{\rho}^2 L_{\mathrm{bt}} V_r \langle \sigma \rangle_{\mathrm{bt}}$$

- **n Yield ∝ ρ^2**
- **n Yield ∝ $\langle\sigma\rangle$**



Heteronuclear deuterated methane CD4 clusters is better than homonuclear D cluster regarding the neutron yield

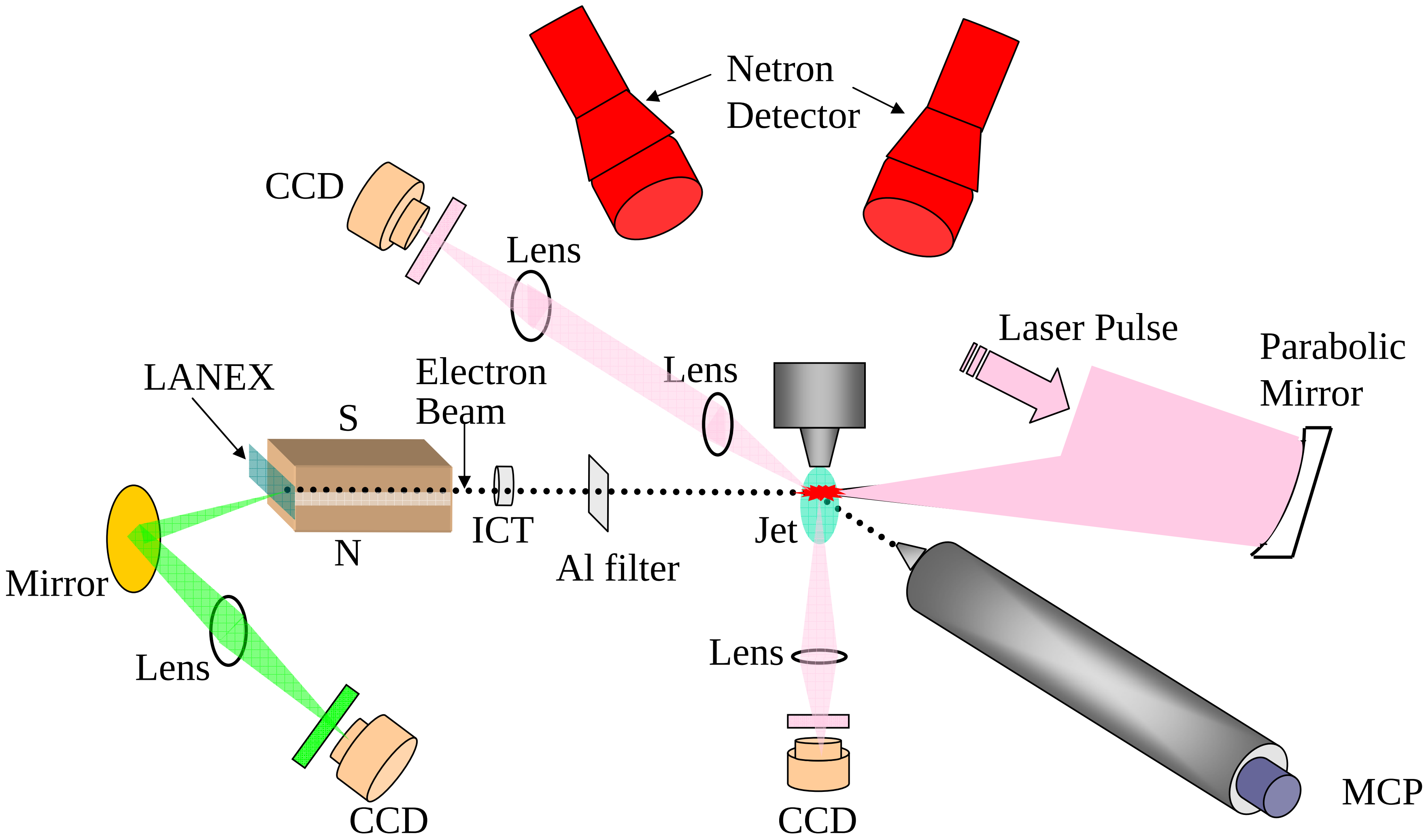


Hongyu Li, Jiansheng Liu *et al.*, J. Phys. B , 40, 3941 (2007)

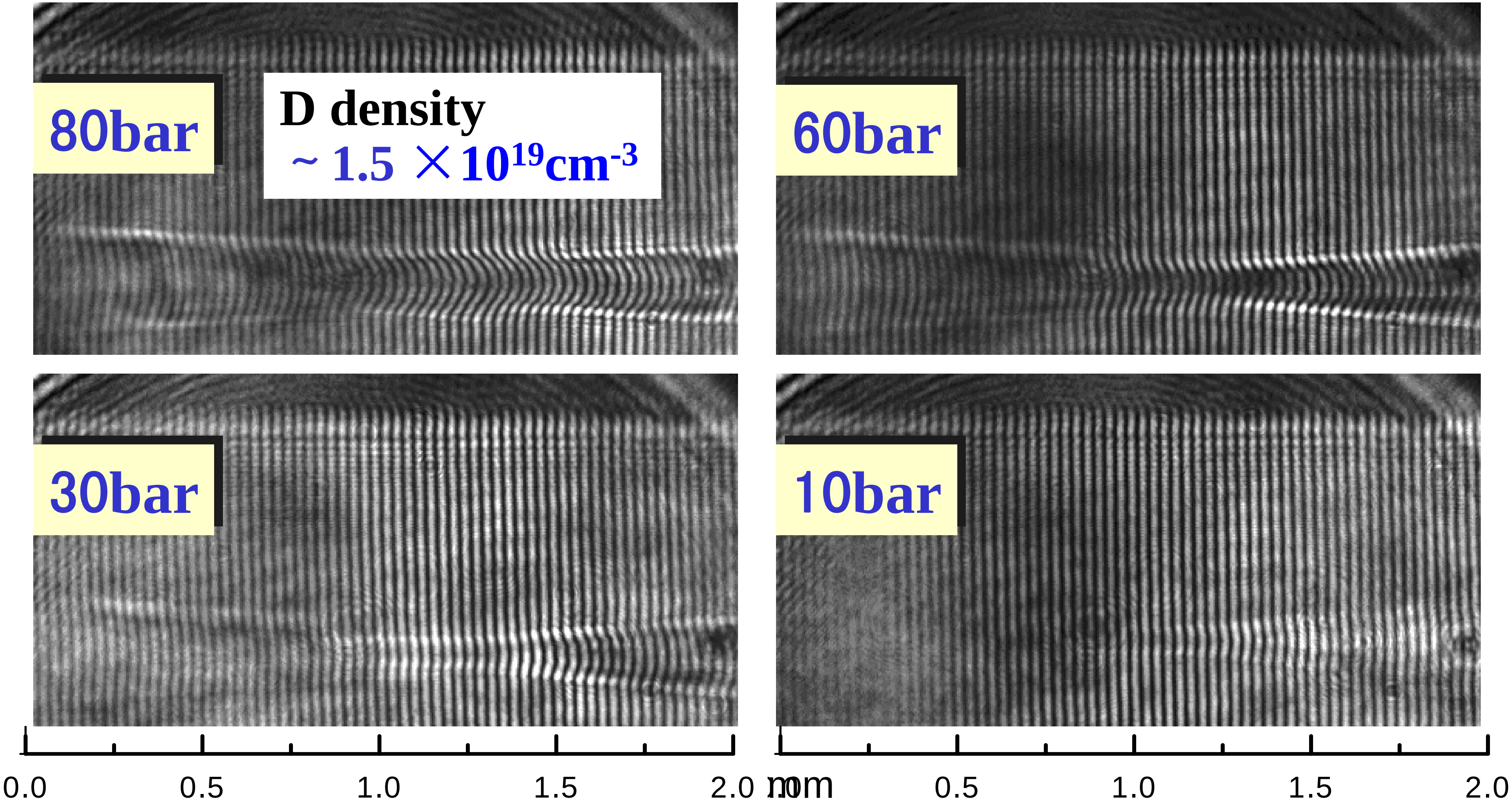
TABLE I. Table-top and medium scale laser driven fusion neutron sources.

Reference	Target	Neutron yield (into 4π)	Laser-pulse parameters Energy (J)	Duration	λ (μm)	I_{peak} (W/cm^2)
[11]	C_8D_8 and D_2 solid	7×10^7	20	1.3 ps	1.054	10^{19}
[12]	C_2D_4 solid	1×10^2	0.2	160 fs	0.79	10^{18}
[13]	CD_2 solid	1×10^7	7.0	0.3 ps	0.529	3.5×10^{19}
[14]	CD_2 solid	1×10^4	0.3	0.05 ps	0.8	2×10^{18}
[15]	C_8D_8 solid	9×10^5	50	500 fs	1.054	2×10^{19}
[16]	CD_2 solid	5×10^4	1.5	1.5 ps	1.055	3×10^{17}
[17]	D_2 gas	1×10^6	62	1 ps	1.05	2×10^{19}
[5]	D_2 clusters	1×10^4	0.12	35 fs	0.82	2×10^{16}
[6]	D_2 clusters	2×10^6	10	100 fs	0.8	2×10^{20}
[7]	CD_4 clusters	7×10^3	0.8	35 fs	0.82	2×10^{17}
[8]	CD_4 clusters	1×10^5	2.5	100 fs	0.8	4×10^{19}

Experimental setup for neutron generation

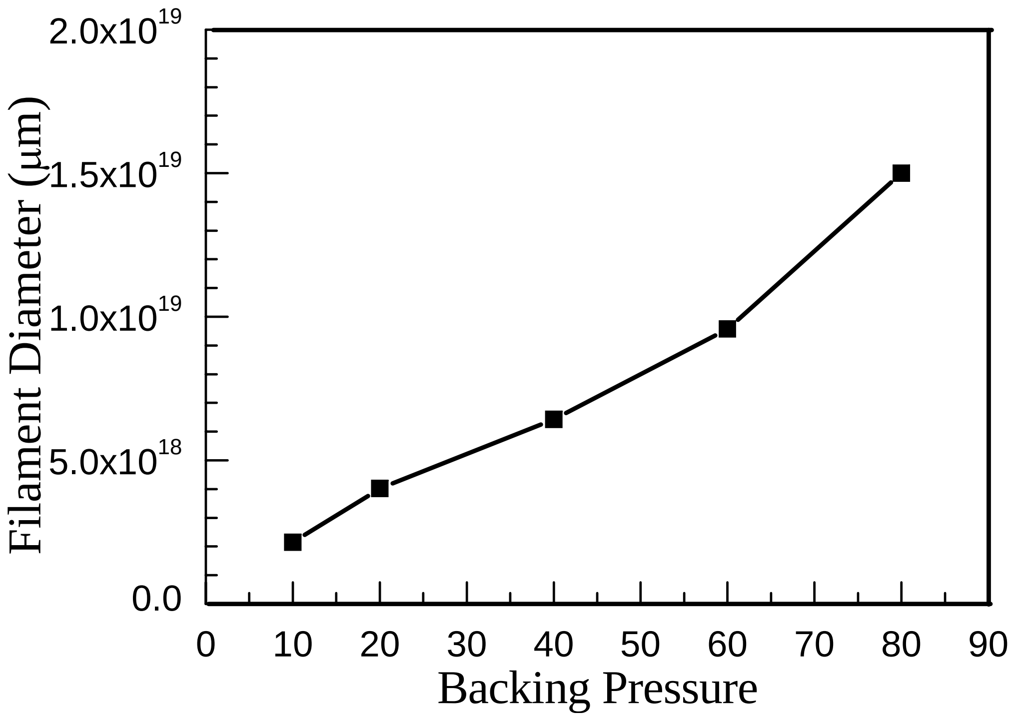


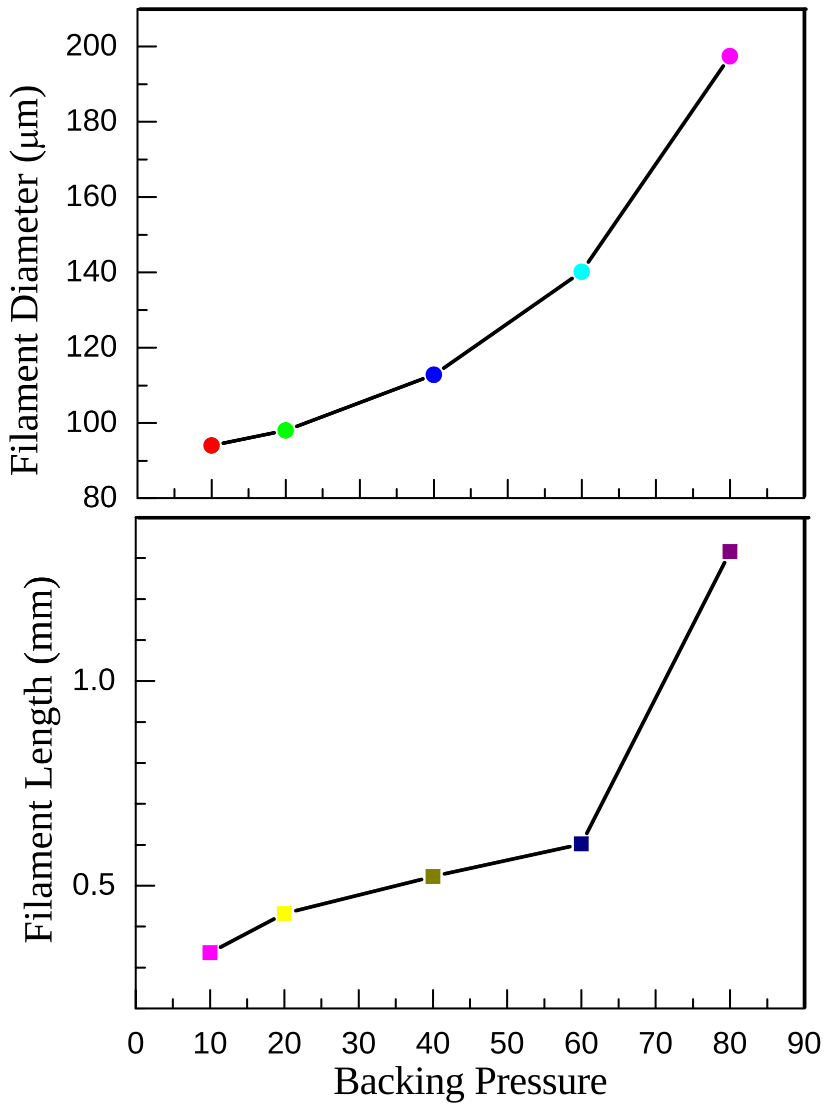
Plasma channel measurement for CD_4 cluster



Laser propagation direction （120mJ， 70 fs）

Deuteron density, channel diameter and length as functions of the backing pressure for CD_4 cluster jet

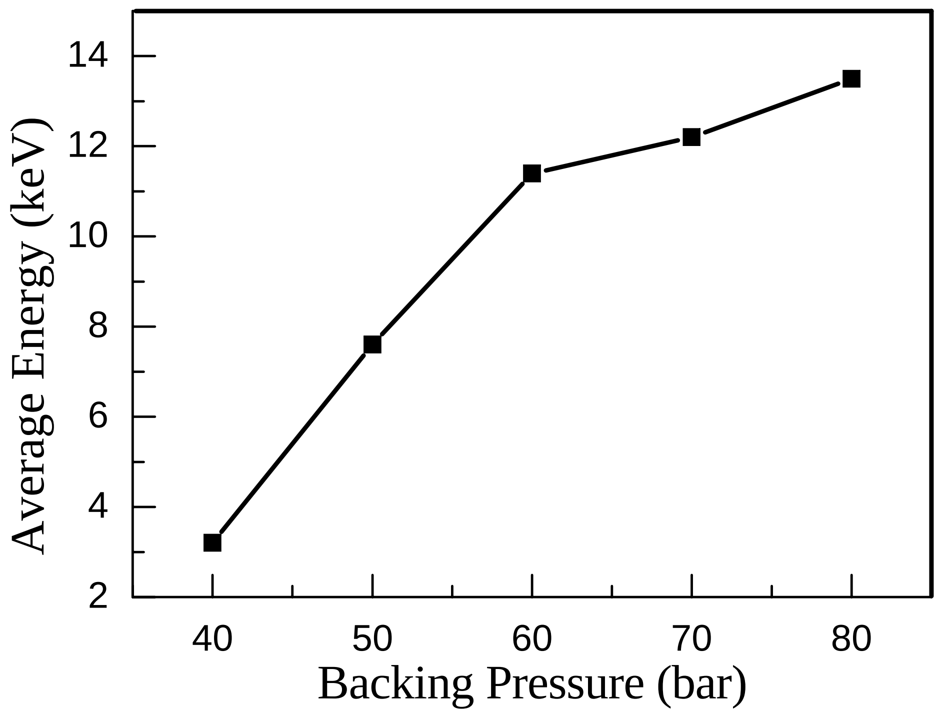


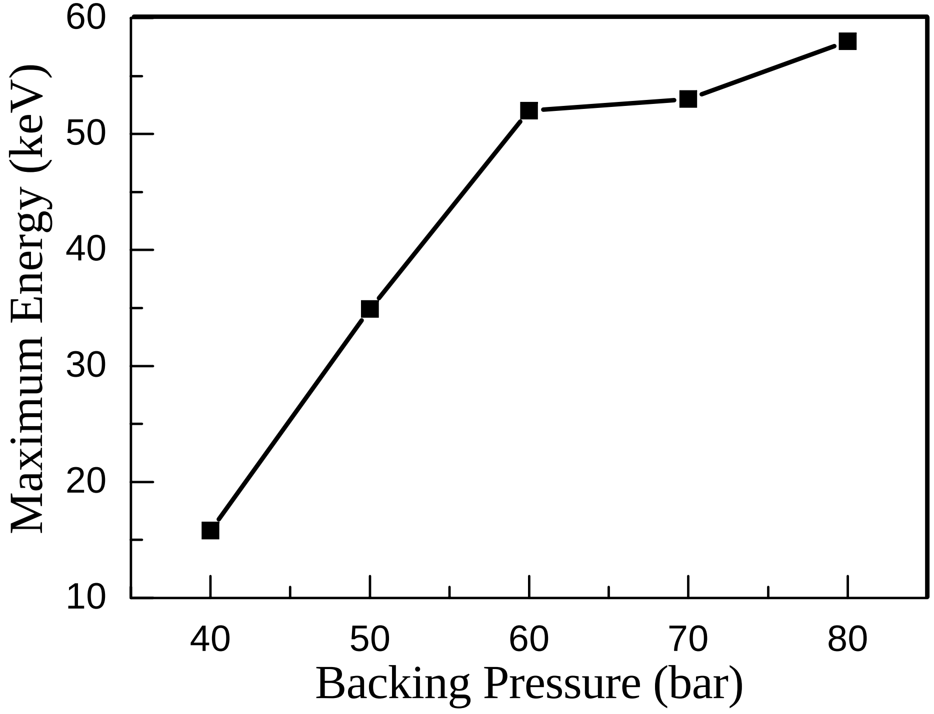


τ = 70fs， E = 120mJ，

I_{peak}=7 × 10^{17}W/cm²

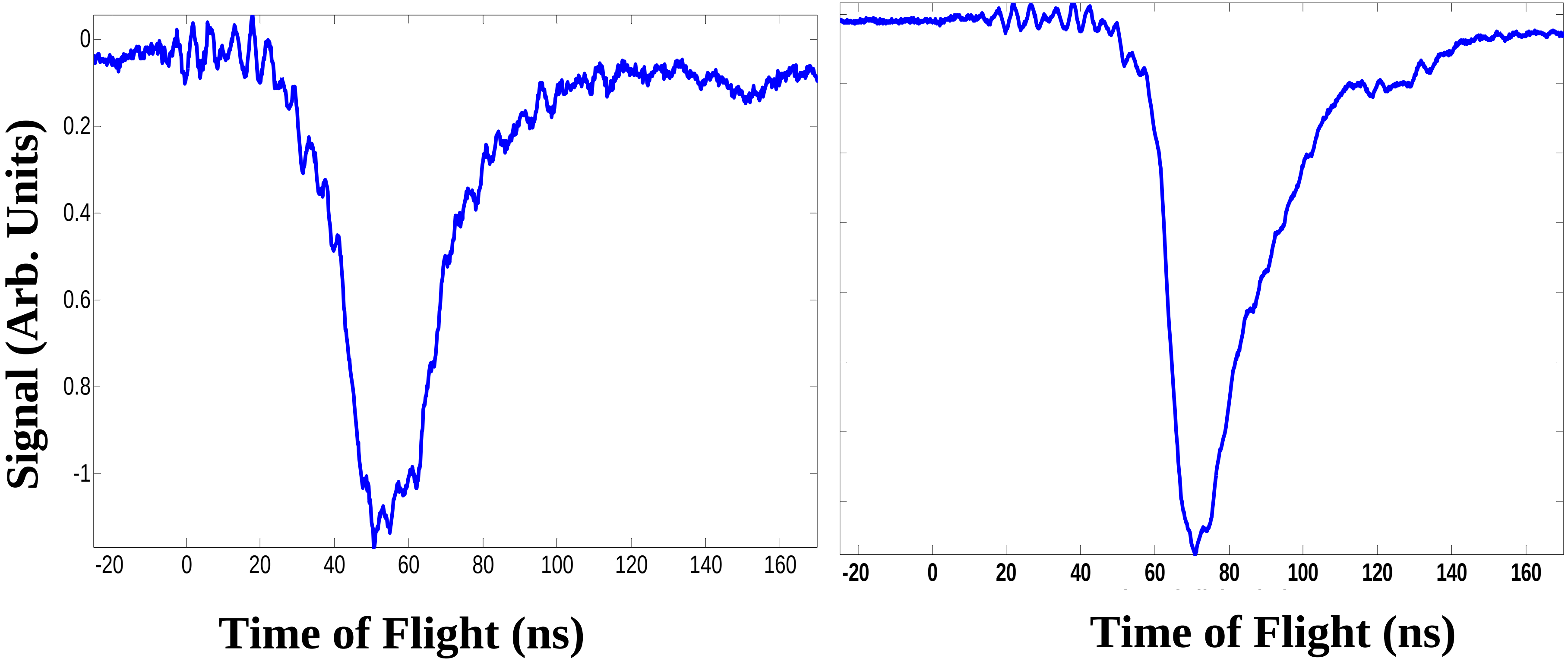
The average and peak energy of Deuteron as functions of the backing pressure for CD4 cluster jet





τ = 70fs， E = 120mJ， I_{peak}=7 × 10^{17}W/cm^2

Neutron energy measurement

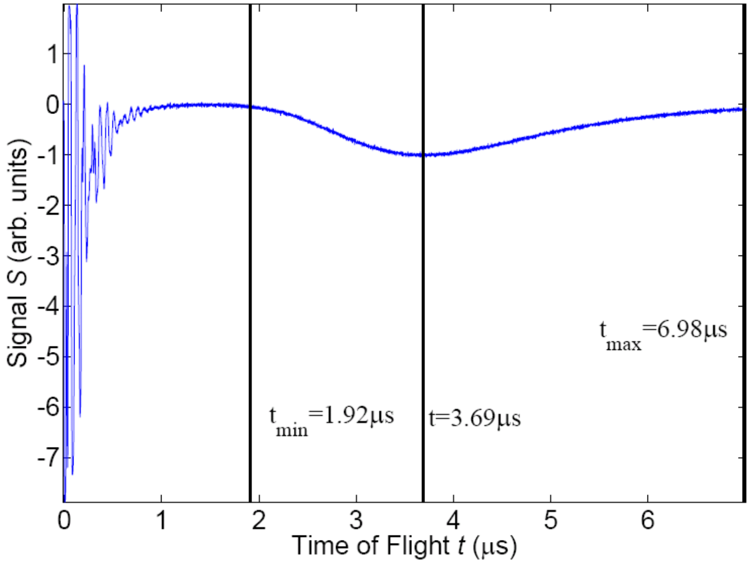


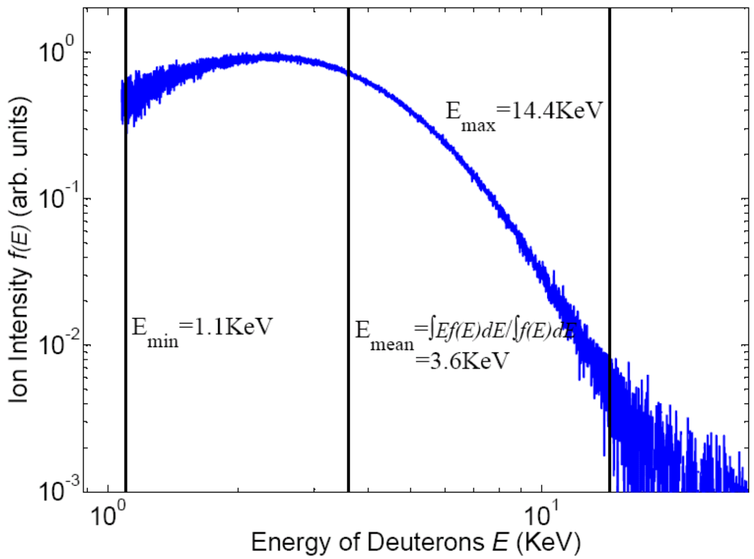
Separation of detector : 50cm， Neutron signal delay: 25ns

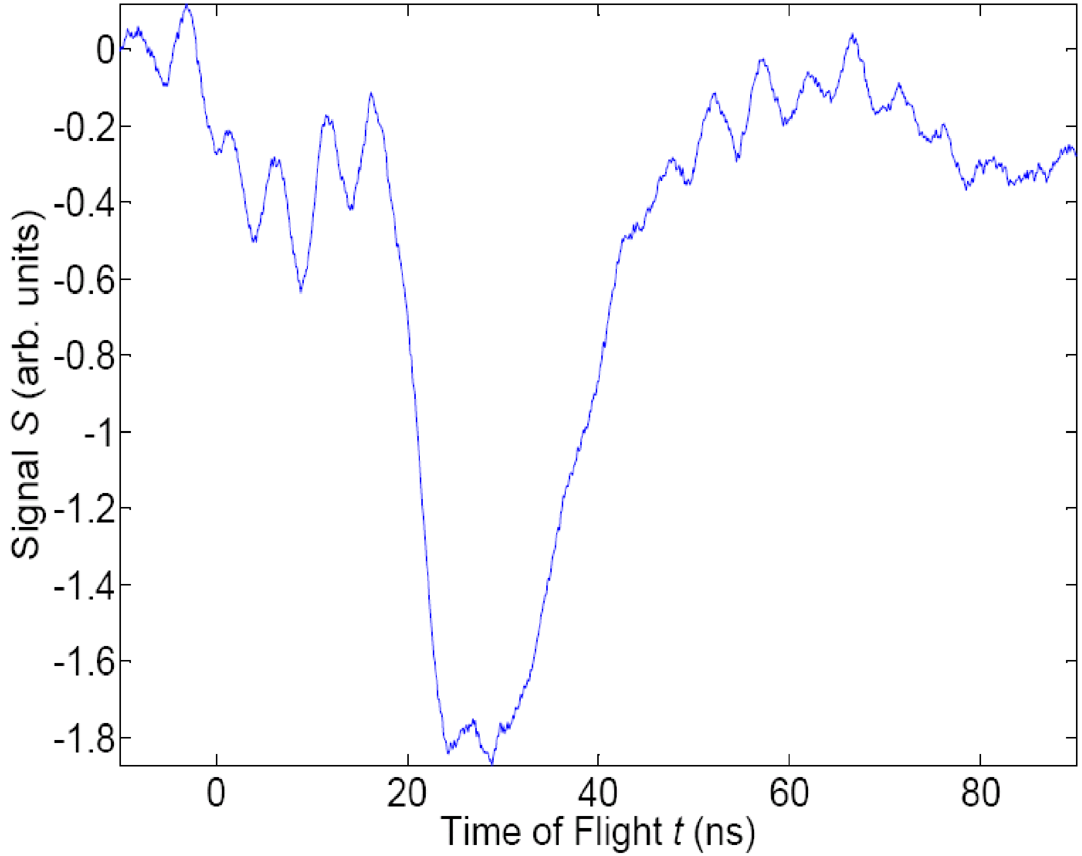
Neutron energy ~2.45MeV

Detector= Plastic scintillators coupled to a photomultiplier tube and then a digital oscilloscope

4×10^4 n/J from Deuterium clusters

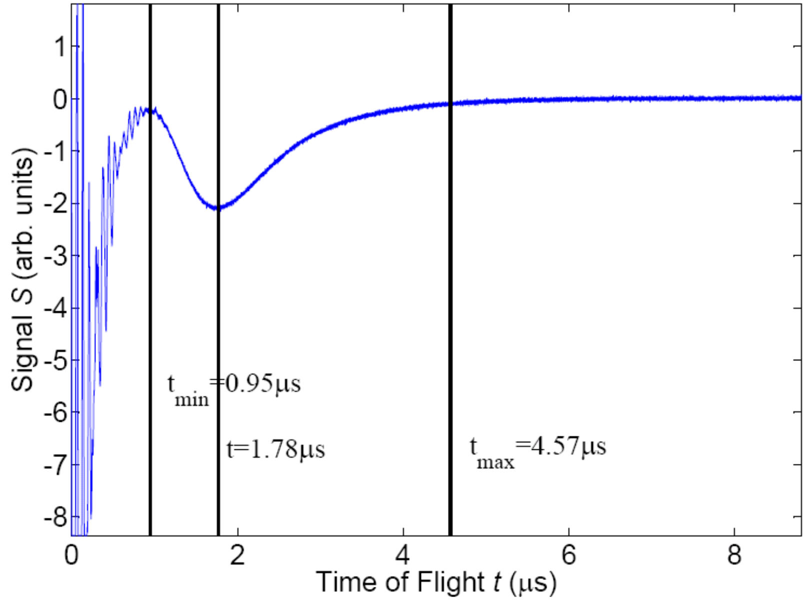


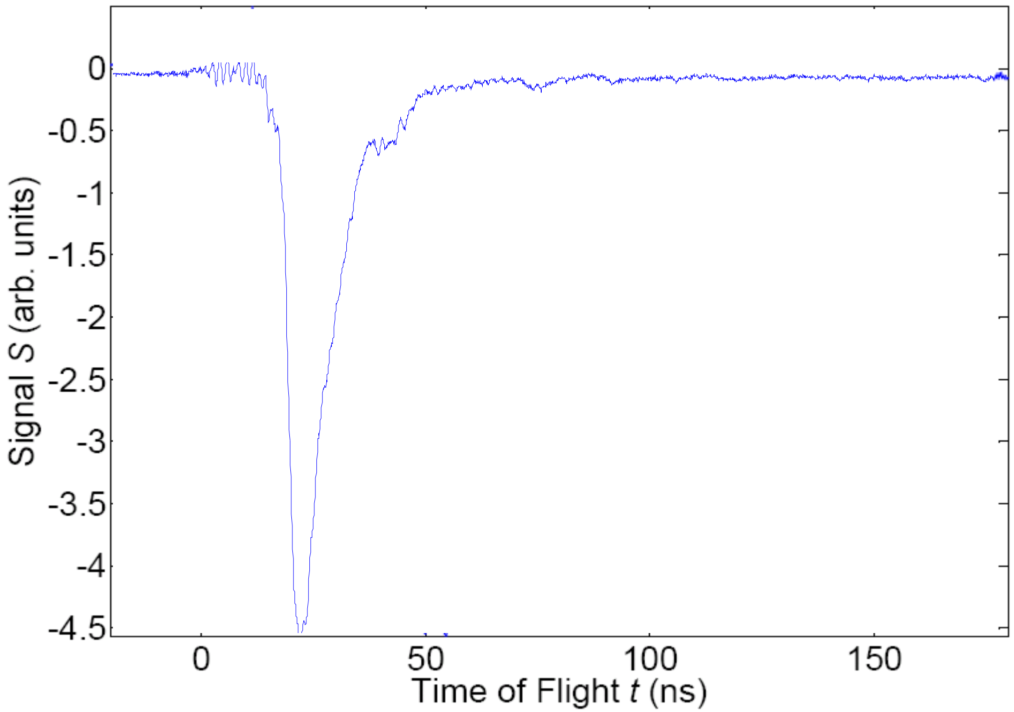


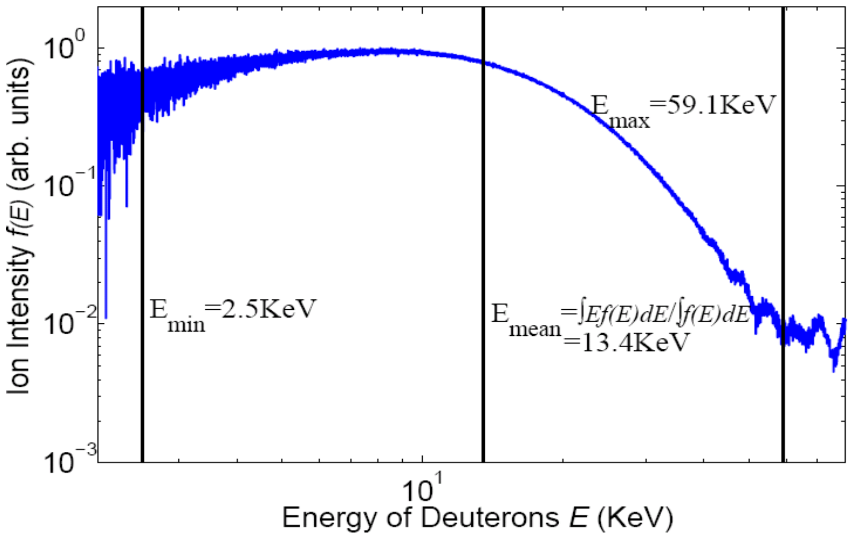


Backing = 64bar， D cluster diameter 12nm， E=160mJ， τ=70fs, n= 6000

2.1 $\times 10^6$ n/J from CD4 clusters



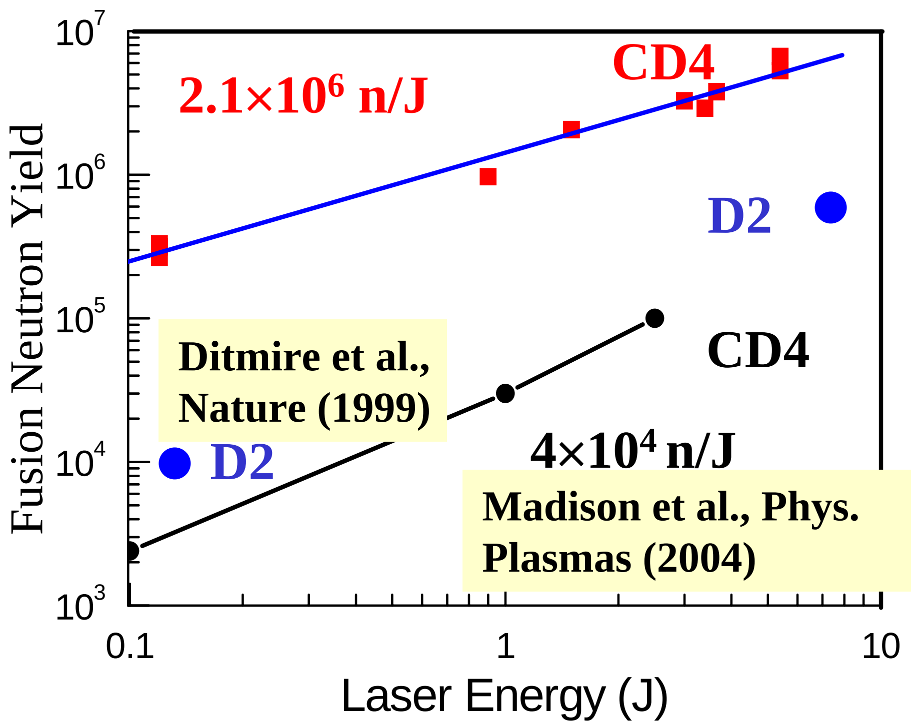


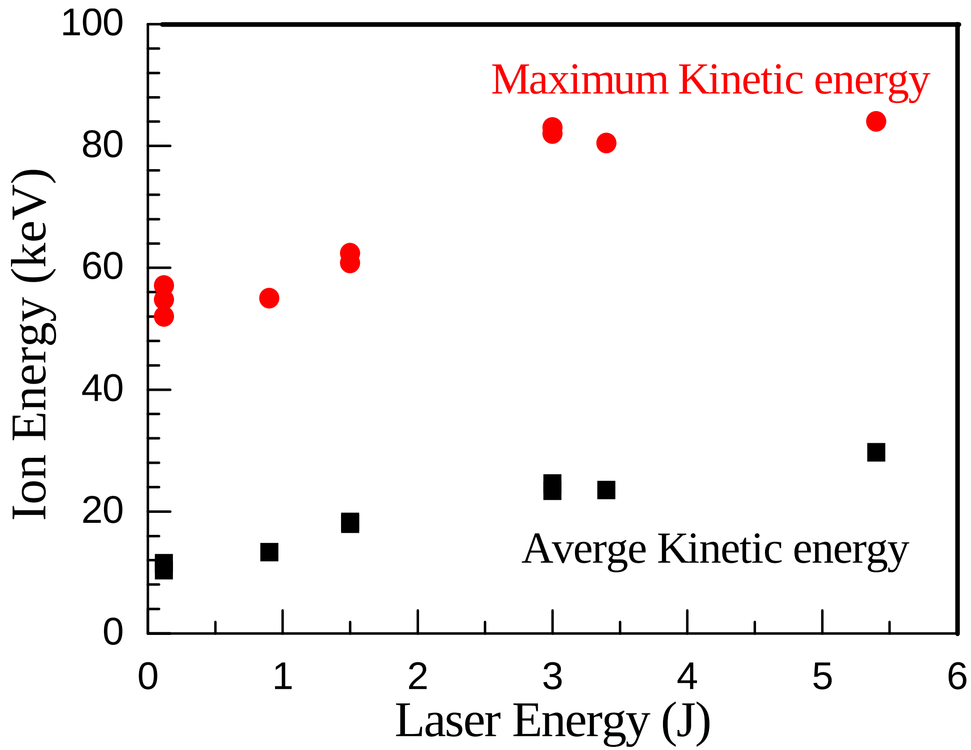


Backing=80bar，
D density >1.5 $\times 10^{19}$cm^{-3} ,
CD4 cluster diameter 12nm，
E=120mJ，τ=70fs。n=2.5×10^5

2.1 $\times 10^6$ neutrons / J laser energy for CD4 cluster

5.5$\times 10^6$ neutrons using a 5.4J//50fs pulse





Backing pressure= 80bar，CD4 diameter =12nm，D density= 1.5 $\times 10^{19}$cm^{-3},
I_{peak}=1.5 × 10^{19}W/cm^2
Laser energy from 120mJ to 5.4J，

Emax for deuteron from 50keV(Eav=10keV) to 90keV(Eav=30keV)

Conclusions

- The electron trajectory control in a shaped laser field and the resulted harmonic emission was investigated using two color and same color double pulses

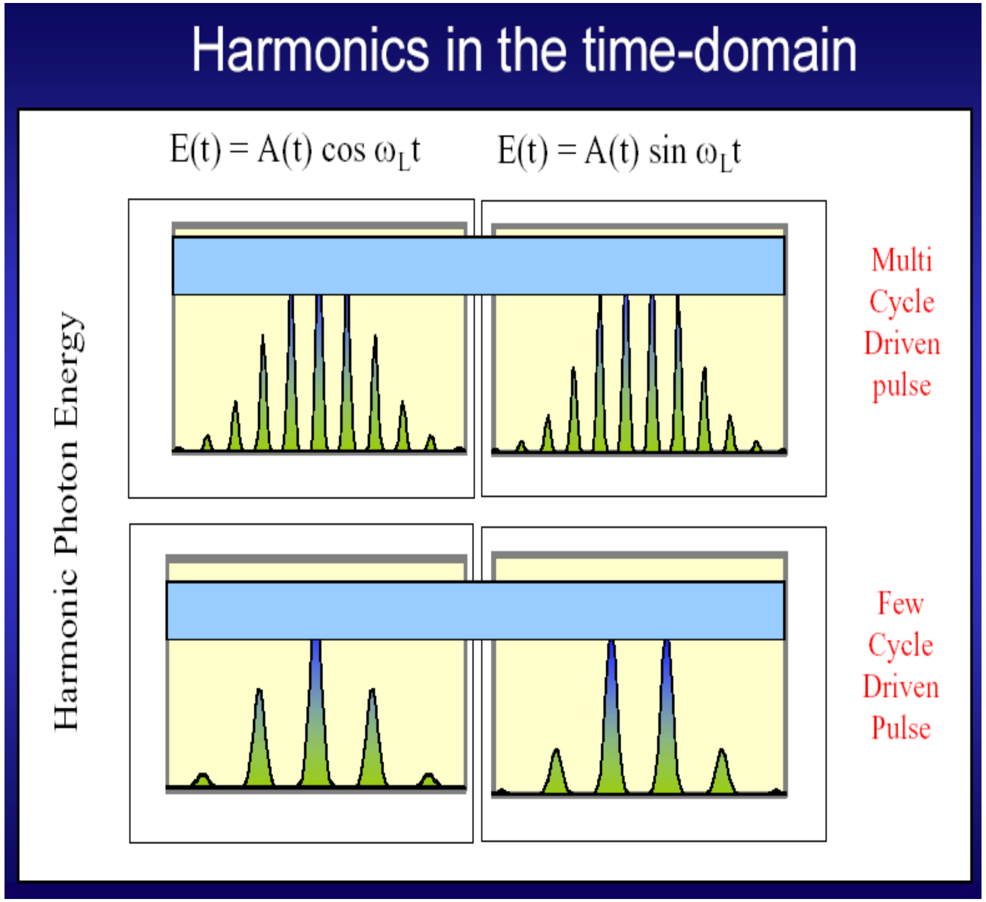
- A delay optimized two-color scheme for producing very short as XUV pulses was proposed. An experimental principle demonstration of this scheme was done. We observed a simultaneous enhancement and broadening of XUV supercontinuum in argon, using 7fs 800nm pulse and its SH.

- We demonstrated that a synthesized laser field consisting of an intense long (multi-optical-cycle) laser pulse and a weak short (few-optical-cycle) laser pulse can temporally confine the HHG emission towards a single strong attosecond pulse.
- It was the first time that the super-continuum at the cutoff region is produced by using strong multi-optical-cycle laser pulses.

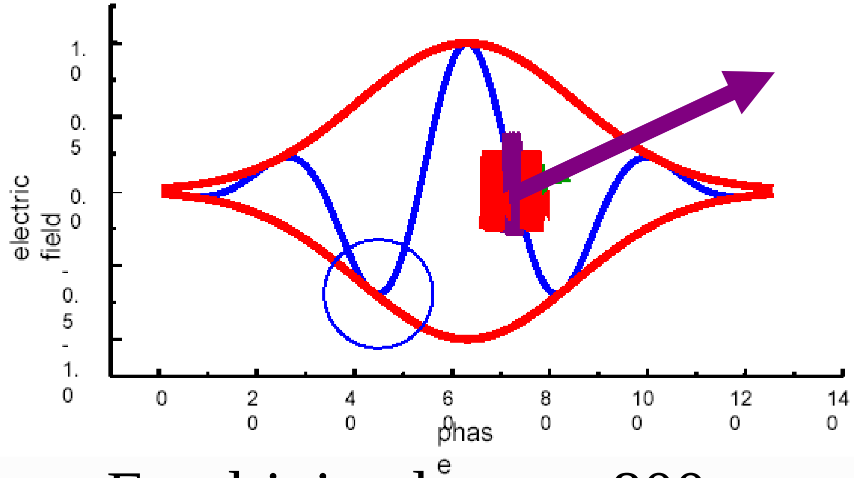
- Table top fusion with D and CD_4 cluster target driven with 100TW laser pulses was demonstrated.
- The matching of laser and cluster parameters is vital for obtaining high energy deuteron and high neutron yield.
- Neutron yield as **2.1×10^6** per J laser energy was demonstrated, with **5.5×10^6** single pulse neutron emission for the driving laser pulse of 5.4J/50fs, verifying the higher conversion efficiency for heteronuclear clusters.

Thank you for your attention!

Generation of isolated single attosecond radiation requires a less than two cycles driving laser pulse



Effect of temporal gating



For driving laser at 800nm

Duration ~ 5 fs

7fs, M. Hentschel et al., Nature, 414, 509 (2001)

5fs(CEP), A. Baltuska et al., Nature, 421, 611 (2003)

A few cycle laser pulse is very weak due to the limitation in compression technology

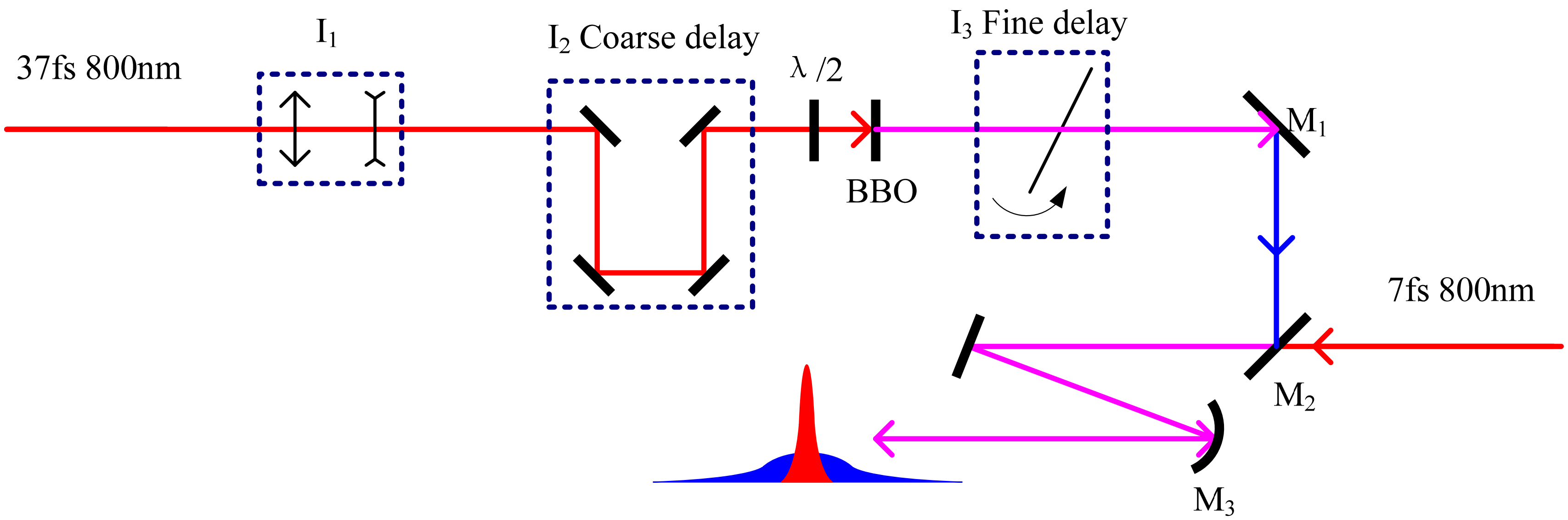
Electron dynamics control in a shaped laser field

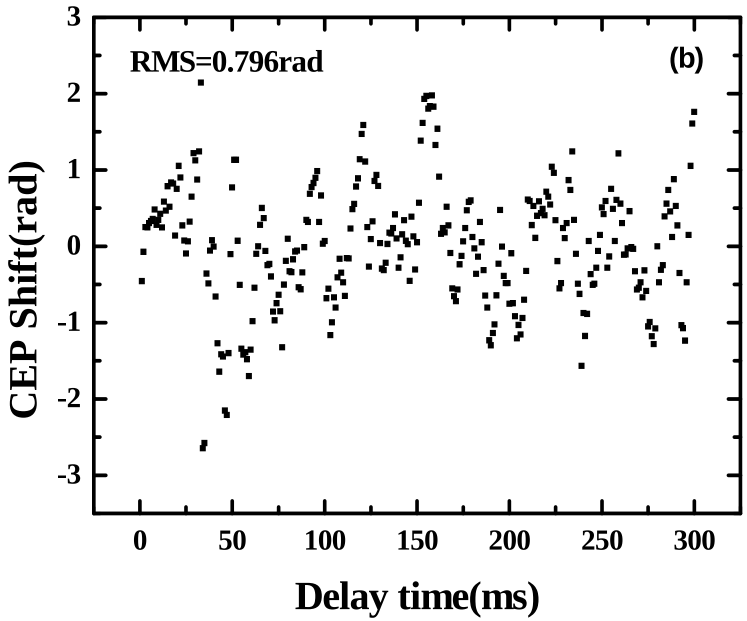
1. Optics Letters 30, 564(2005)双色场电离
2. Optics Express 13, 9897(2005)双色场偏振控制

3. Physical Review Letters 98, 203901(2007)双色场优化时间延迟理论
4. Optics Letters 33, 234(2008)双色场优化时间延迟实验
5. Physical Review A77, 023416 (2008)双色场选择轨道
6. J. Phys. B 41, 115601(2008)双色场偏振控制
7. J. Phys. B 41, 215601(2008)双色场长脉冲

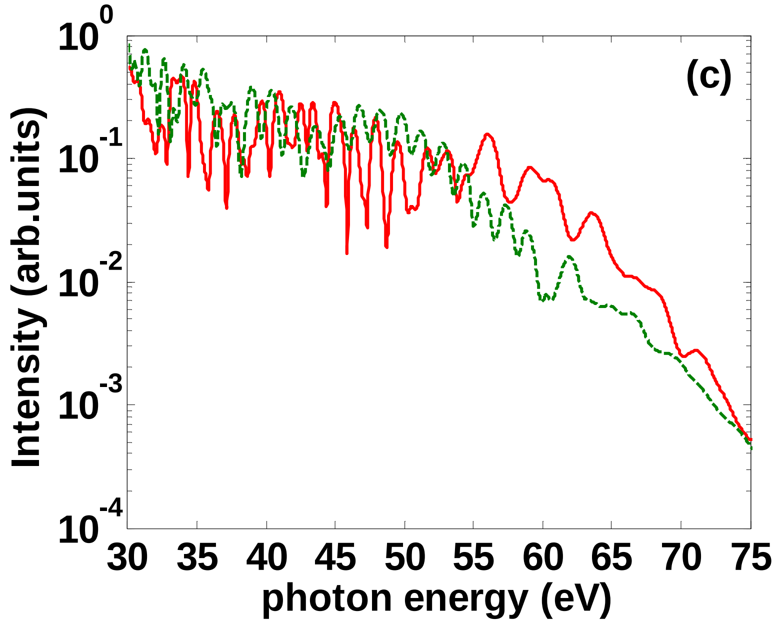
8. Physical Review A70, 053809(2004)双脉冲理论
9. Physical Review A75, 051802(R)(2007)双脉冲实验

10. Physical Review A78, 015802 (2008)分子中电子相干的强度控制



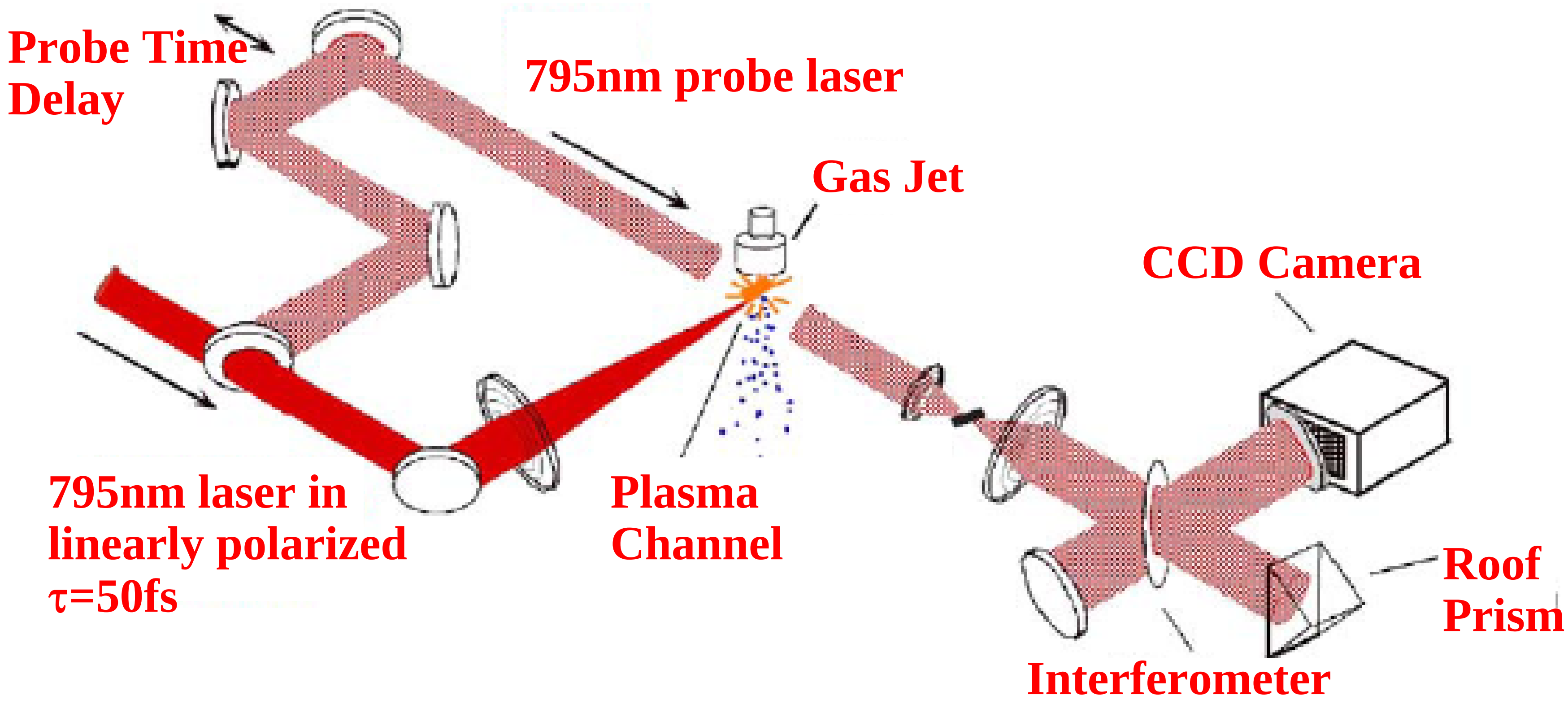


The CEP spread of the amplified laser pulses

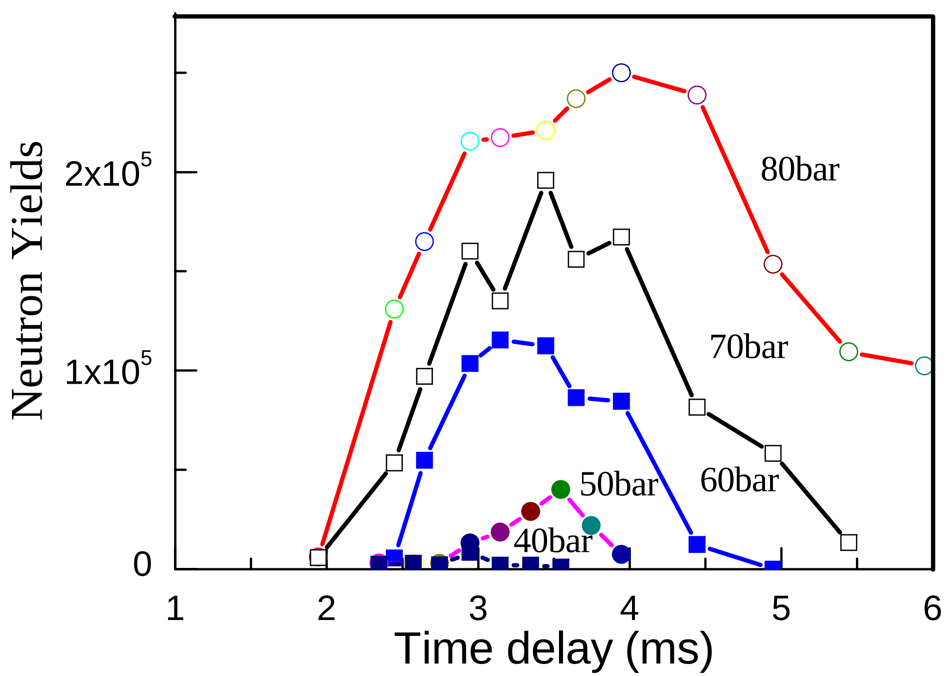


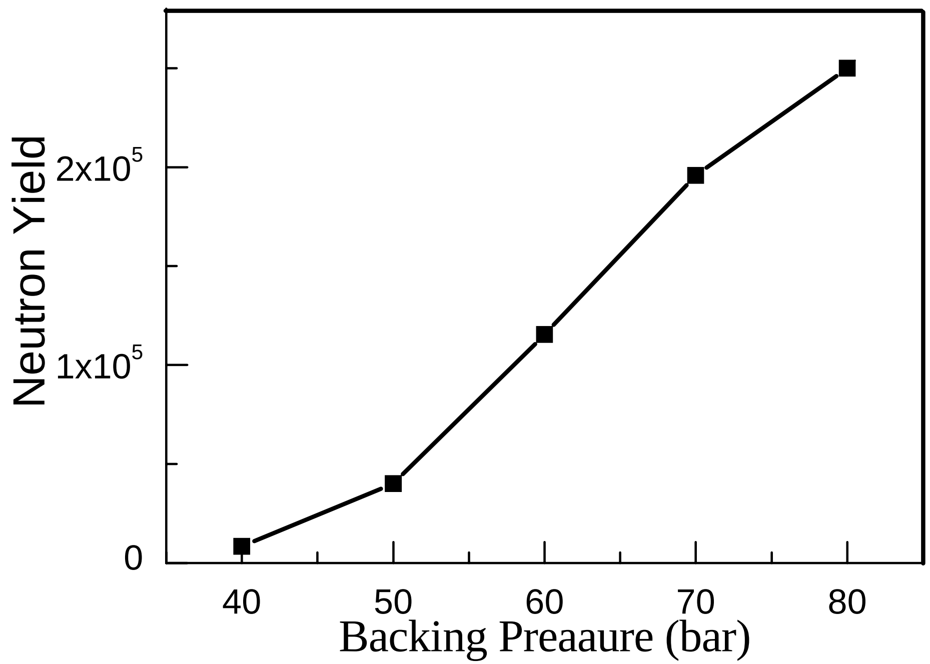
Calculated spectra with different two-color delay considering CEP jitter

Plasma channel measurement by Pump-Probe interferometer



Neutron yield for CD4 as functions of backing pressure and time delay





τ = 70fs， E = 120mJ， I_{peak}=7 × 10^{17}W/cm^2