HEP 2021

Jan 15, 2021

Generation of Single Cycle Tunable Radiation Pulses from THz to Mid-IR Using Frequency Downshifting in Plasma Wakes

Zan Nie,[1] Yipeng Wu,[1] Chaojie Zhang,[1] Warren B. Mori,[1] Chan Joshi[1]

Wei Lu,[2] Chih-Hao Pai,[2] Jianfei Hua,[2] Jyhpyng Wang[3]

1. University of California, Los Angeles, USA

2. Tsinghua University, China

3. National Central University, Taiwan

Collaborators

Yipeng Wu, Chaojie Zhang, Fei Li,
Warren Mori, Chan Joshi

Jie Zhang, Xiaonan Ning, Yunxiao He, Zhi Cheng,
Qianqian Su, Shuang Liu, Yue Ma,
Chih-Hao Pai, Jianfei Hua, Wei Lu

Hsu-Hsin Chu and Jyhpyng Wang

Outline

UCLA

- Background
- Frequency downshifting in a nonlinear plasma wake
  - Mid-IR pulses (3-20 μm) using Ti:sapphire lasers
  - THz pulses (2-12 THz, or 25-150 μm) using CO_2 lasers
- Summary

Near-IR → Mid-IR → THz

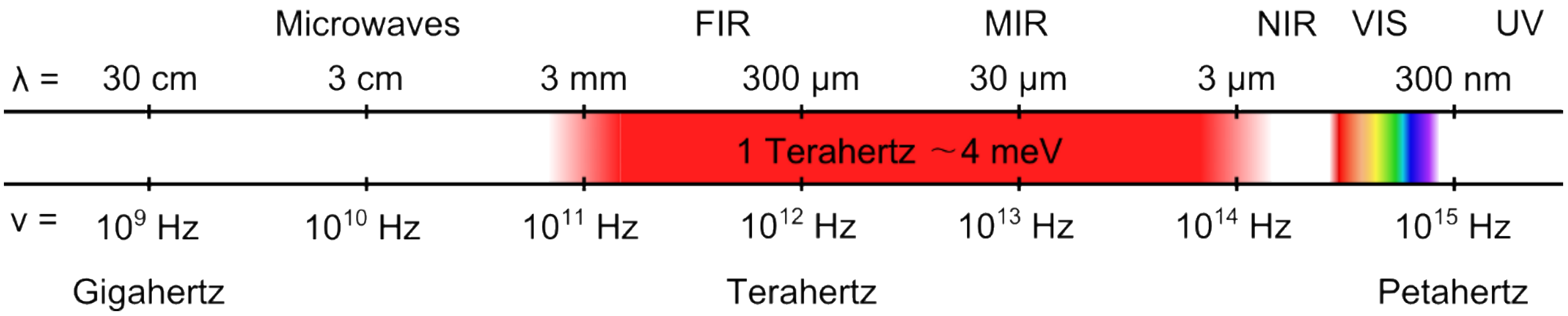
NIR
~1 μm
~300 THz

→

MIR
2-20 μm
150-15 THz

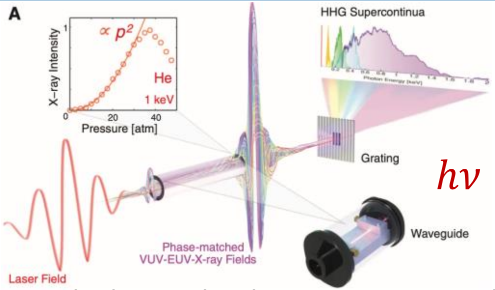
→

THz
30-3000 μm
10-0.1 THz



Applications of ultra-short mid-IR/THz pulses

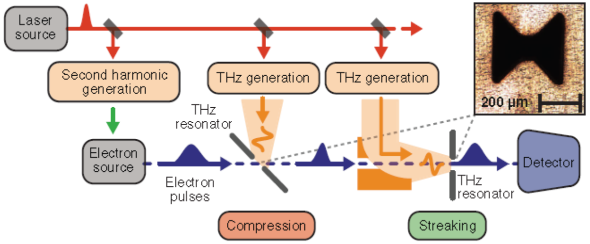
HHG & Attosecond science



$h\nu \propto \lambda^2$

T. Popmintchev, et al. *Science* 336, 1287-1291 (2012)

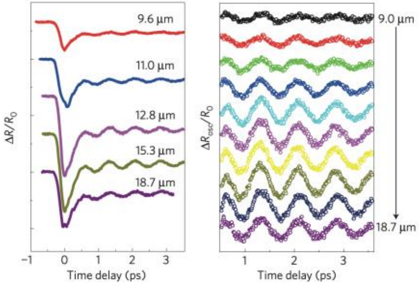
THz streaking



C. Kealhofer, et al. *Science* 352, 429-433 (2016)

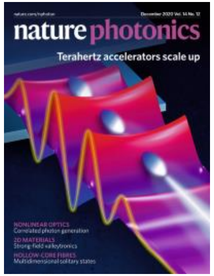
Intense MIR/THz pulses

Pump-probe experiments



M. Först , et al. *Nat. Phys.* 7, 854-856 (2011)

THz acceleration



M. T. Hibberd, et al. *Nat. Photon.* 14, 755-759 (2020)

Conventional ultra-short mid-IR/THz sources

UCLA

Mid-IR sources

- OPA/OPCPA[1]
- DFG[2]
- Two-color filamentation[3]
- CO_2 lasers[4]

THz sources

- Optical rectification[5]
- DFG[6]
- Two-color filamentation[7]
- Laser-solid interaction[8]

Plasma (frequency converter)

[1] Y. Fu, et al. Appl. Phys. Lett. 112, 241105(2018)

[2] P. Krogen, et al. Nat. Photonics 11, 222(2017)

[3] T. Fuji, et al. Opt. Lett. 32, 3330(2007)

[4] D. Haberberger, et al. Opt. Express, 18, 17865(2010)

[5] C. Vicario, et al. Opt. Lett. 39, 6632 (2014)

[6] A. Sell, et al. Opt. Lett. 33, 2767-2769 (2008)

[7] A. D. Koulouklidis et al. Nat. Commun. 11, 292 (2020)

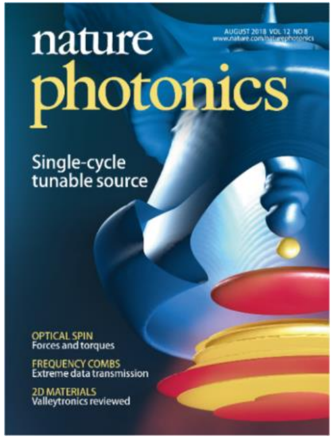
[8] G. Liao, et al. PNAS 116, 3994-3999 (2019)

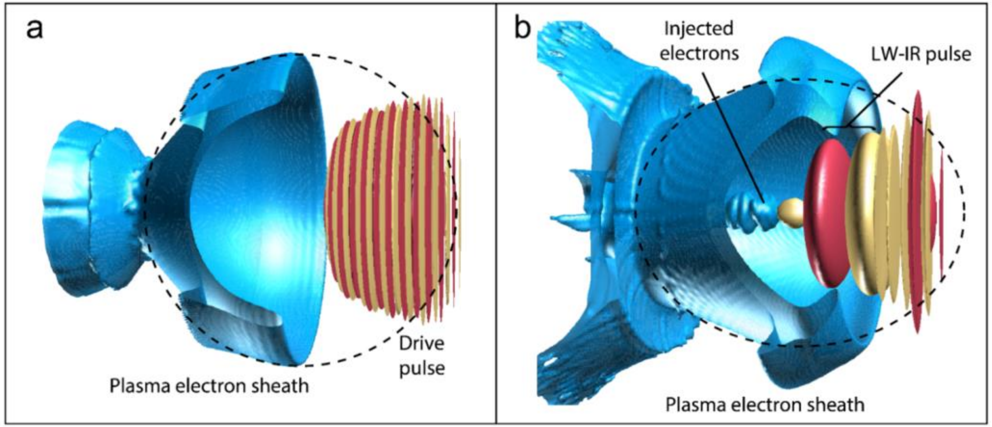
Laser wakefield acceleration (LWFA)

Laser → **Plasma** → **Particle**

Photon Deceleration
(Asymmetric SPM)

Particle Acceleration
(LWFA)

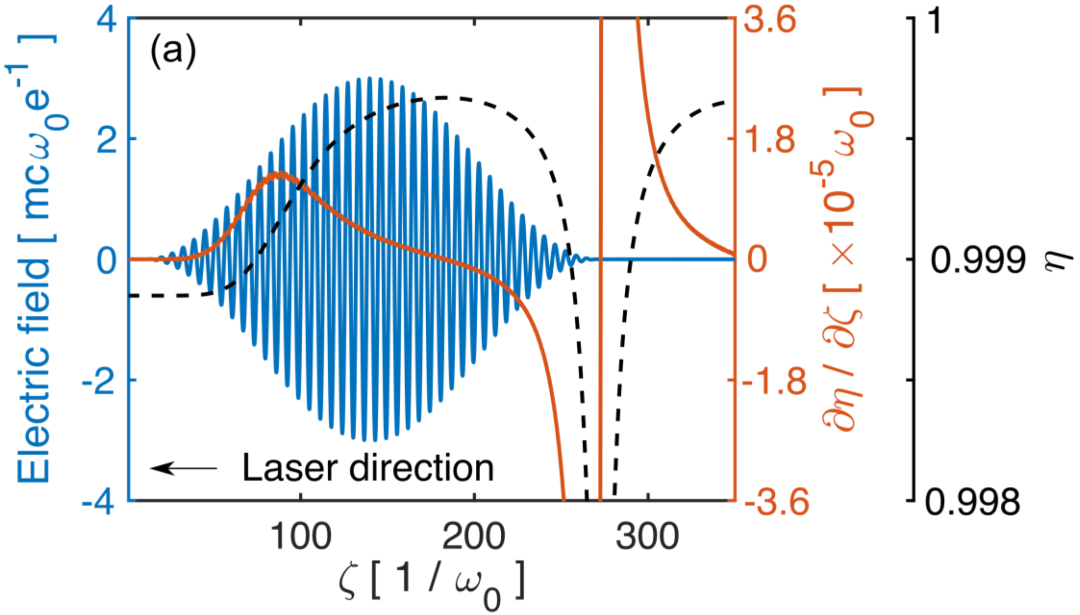




Z. Nie, et al. *Nature Photonics* **12**, 489-494 (2018)

Photon deceleration

UCLA



$$\frac{1}{\omega}\frac{\partial\omega}{\partial t} = -\frac{\partial\eta}{\partial\zeta}$$

$$(\zeta = t - \frac{z}{c})$$

$$\eta \simeq 1 - \frac{\omega_p^2}{2\omega^2}\frac{1}{1+\phi}$$

Theory and simulations:

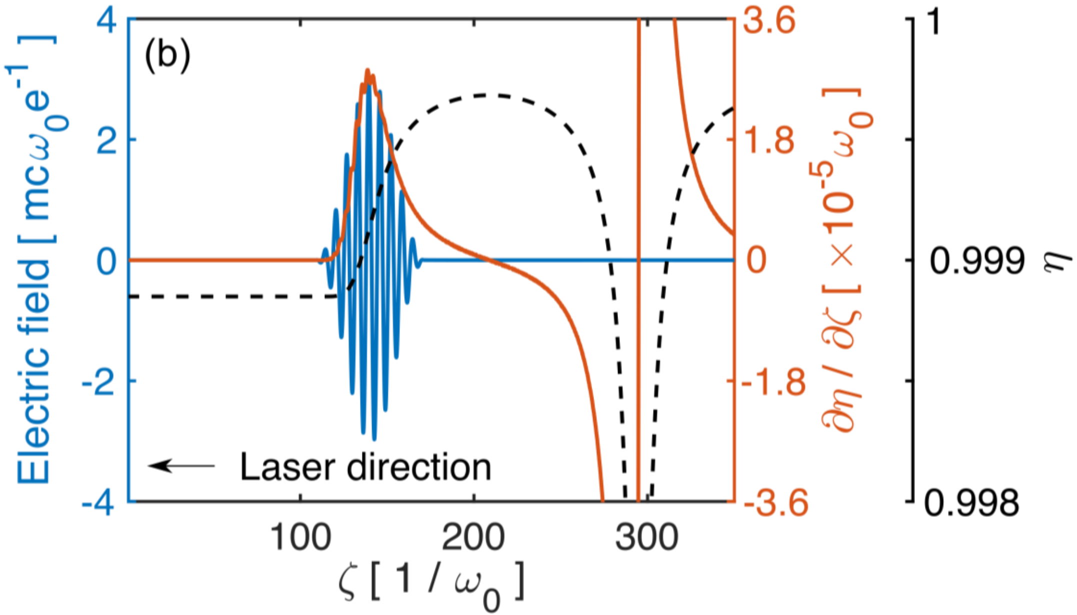
- S. C. Wilks, et al. Phys. Rev. Lett. 62, 2600 (1989)
- P. Sprangle, et al. Phys. Rev. Lett. 64, 2011 (1990)
- W. B. Mori, IEEE J. Quantum Electron. 33, 1942(1997)
- F. S. Tsung, et al, PNAS 99, 29-32 (2002)
- Gordon, D. F. et al. Phys. Rev. Lett. 90, 215001 (2003)
- W. Zhu, et al, Phys. Plasmas 19, 033105 (2012)
- W. Zhu, et al, Phys. Plasmas 20, 073103 (2013)

Experiments:

- J. Faure, et al. Phys. Rev. Lett. 95, 205003 (2005)
- J. Schreiber, et al. Phys. Rev. Lett. 105, 235003 (2010)
- C.-H. Pai, et al. Phys. Rev. A 82, 63804 (2010)

Photon deceleration

UCLA



$$\frac{1}{\omega}\frac{\partial\omega}{\partial t} = -\frac{\partial\eta}{\partial\zeta}$$

$$\left(\zeta = t - \frac{z}{c}\right)$$

$$\eta \simeq 1 - \frac{\omega_p^2}{2\omega^2}\frac{1}{1+\phi}$$

By our theoretical estimation, the optimal pulse duration for MIR pulse generation is:

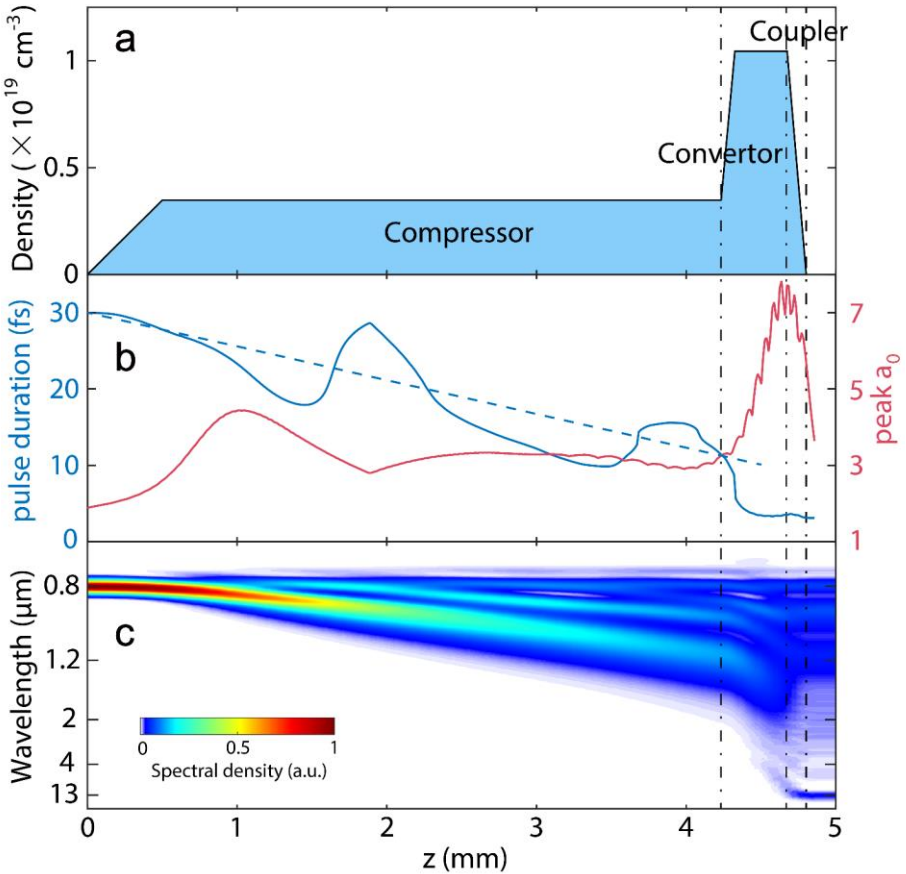
$$c\tau \simeq \frac{0.52\lambda_{\mathrm{p}}}{a_0} \qquad (a_0 \gg 1)$$

For instance:

$$\begin{cases} n_{\mathrm{p}} = 4 \times 10^{18}\ \mathrm{cm}^{-3} \\ a_0 = 3 \end{cases}$$

$$\Longrightarrow \quad \tau = 9.6\ \mathrm{fs}$$

Photon deceleration in a tailored plasma structure

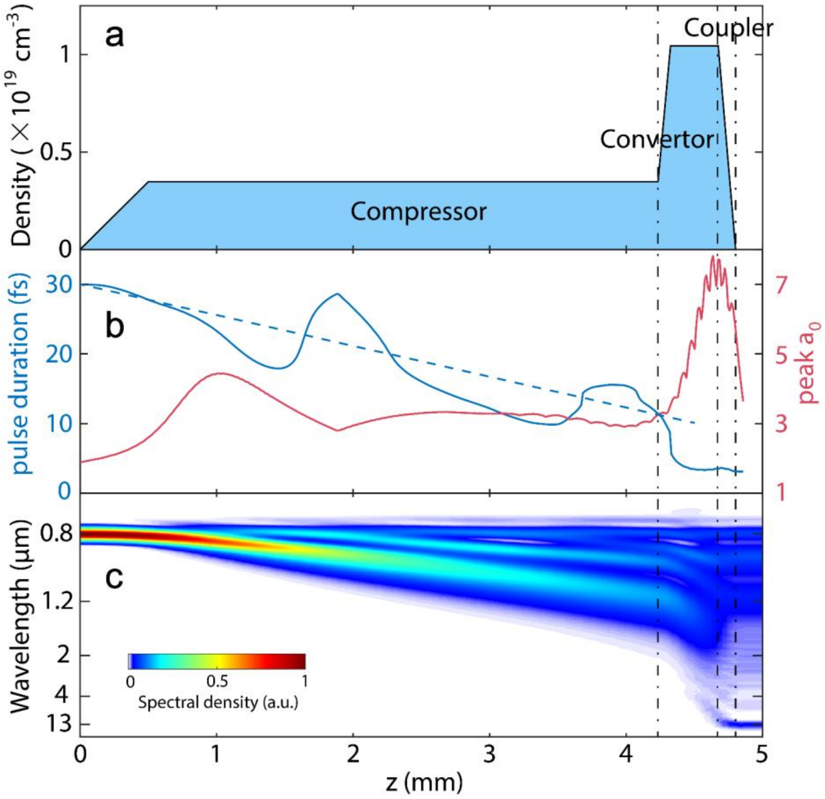


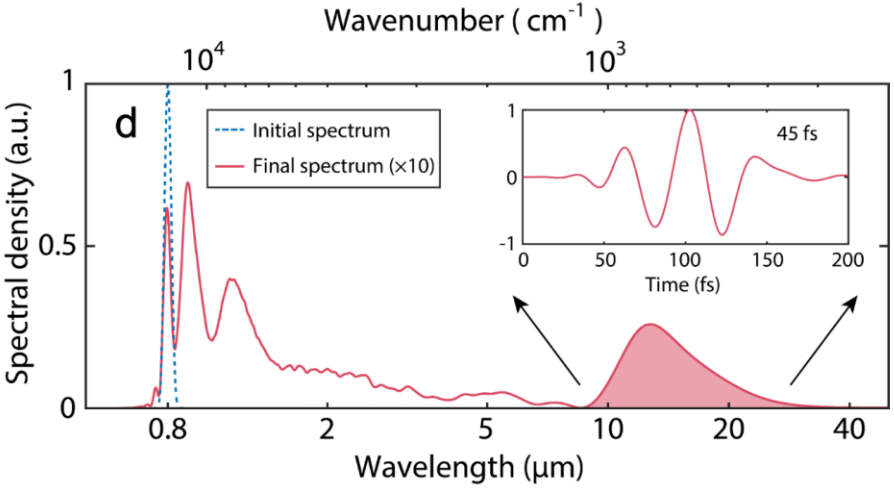
Osiris 3D simulation:

Wavelength	800 nm
Energy	1.2 J
Pulse duration (FWHM)	30 fs
Spot size w_0	16 µm

Z. Nie, et al. *Nature Photonics* **12**, 489-494 (2018)

Photon deceleration in a tailored plasma structure





0.8 μm 30 fs 1.2 J	**1.7%** →	12 μm 45 fs 20 mJ

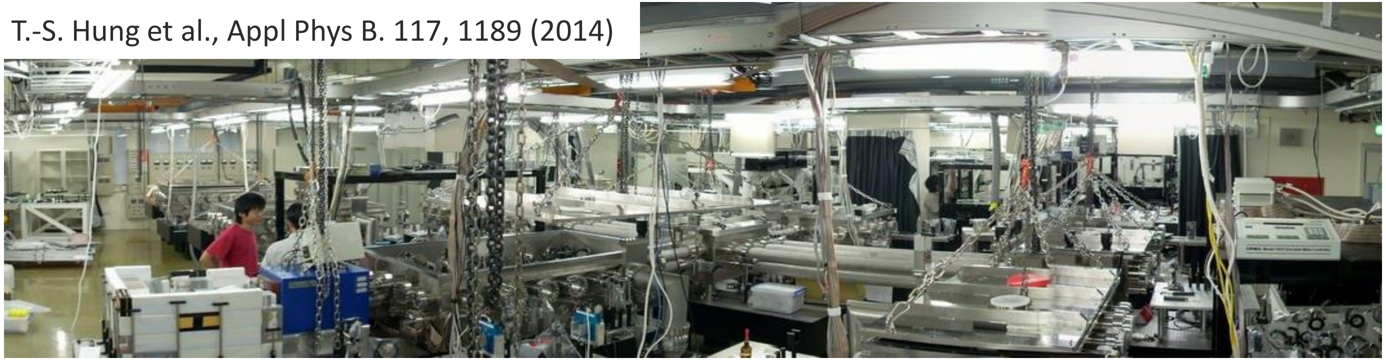
Z. Nie, et al. *Nature Photonics* **12**, 489-494 (2018)

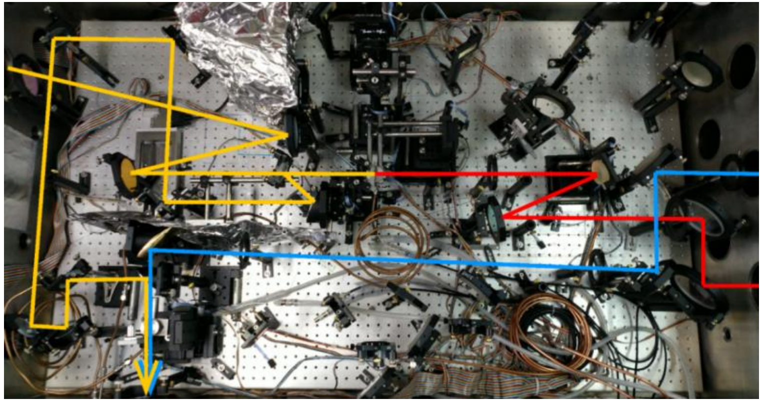
Experimental setup

UCLA

100 TW laser platform at National Central University, Taiwan

T.-S. Hung et al., Appl Phys B. 117, 1189 (2014)





Main beam

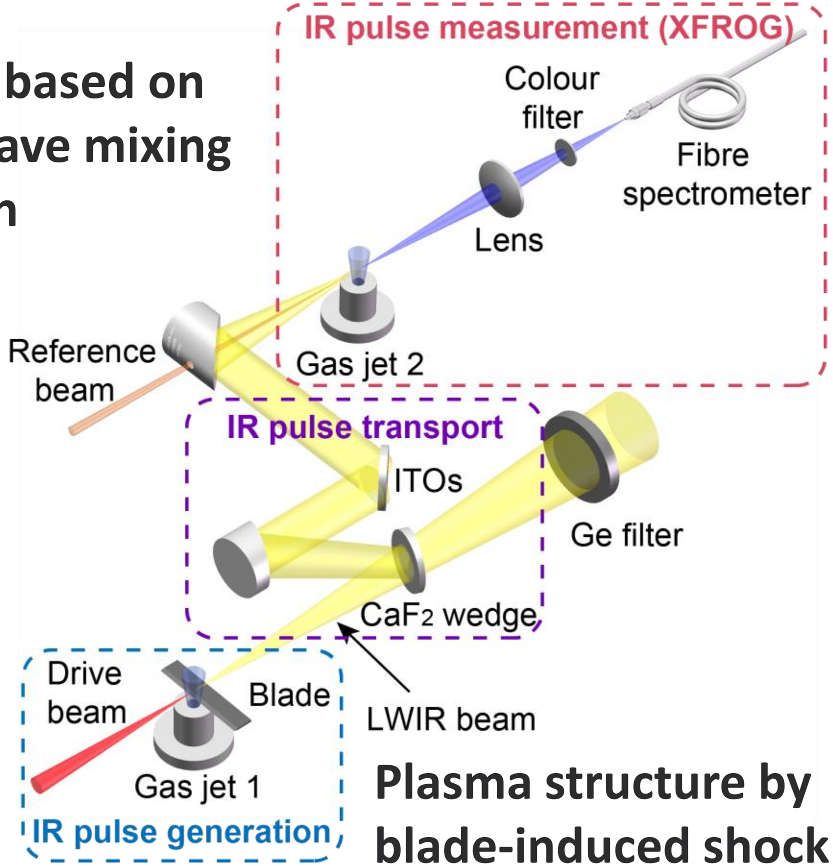
Reference beam

MIR beam

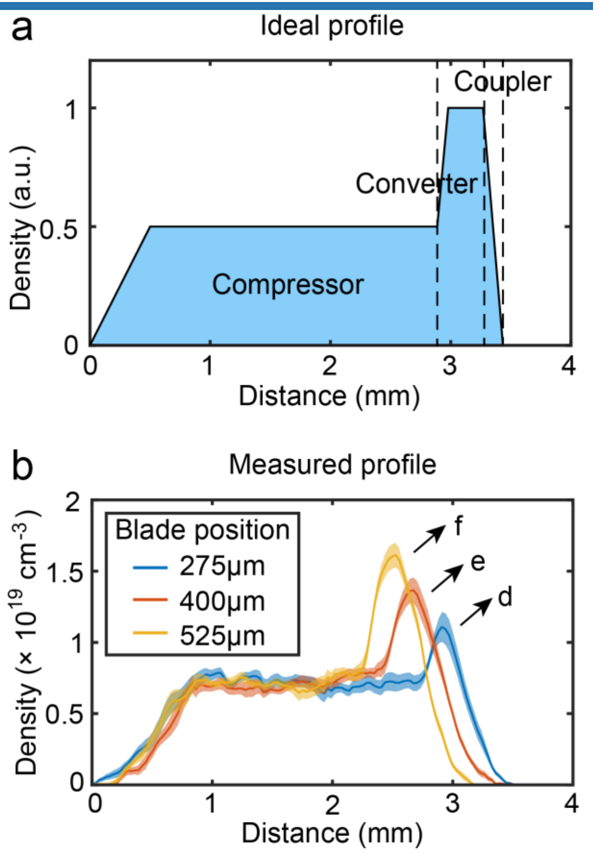
Experimental setup (schematic)

UCLA

XFROG based on Four-wave mixing in argon

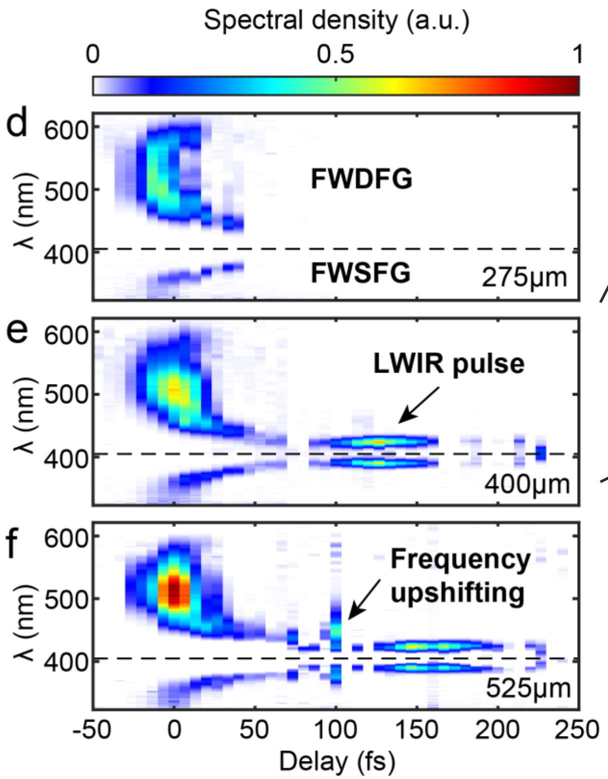


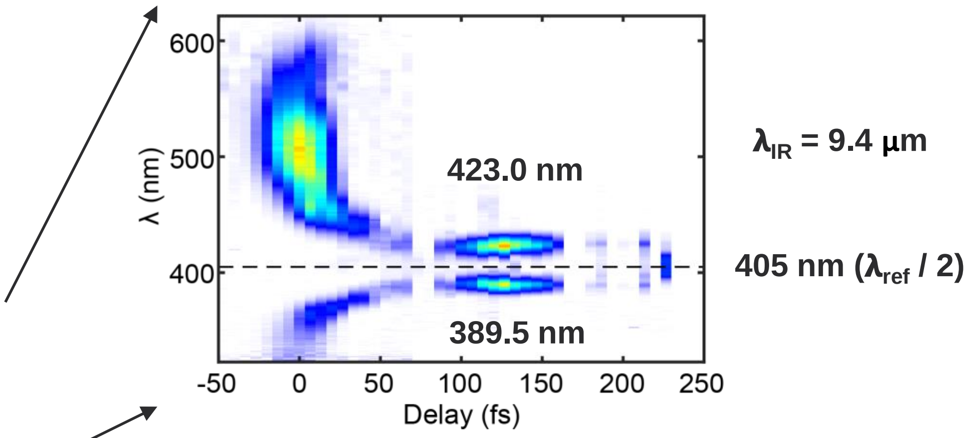
Plasma structure by blade-induced shock



Z. Nie, et al. Nature Communications **11**, 2787 (2020)

XFROG results





FWDFG $\omega_{\mathrm{ref}} + \omega_{\mathrm{ref}} - \omega_{\mathrm{IR}} = \omega_{\mathrm{FWDFG}}$

FWSFG $\omega_{\mathrm{ref}} + \omega_{\mathrm{ref}} + \omega_{\mathrm{IR}} = \omega_{\mathrm{FWSFG}}$

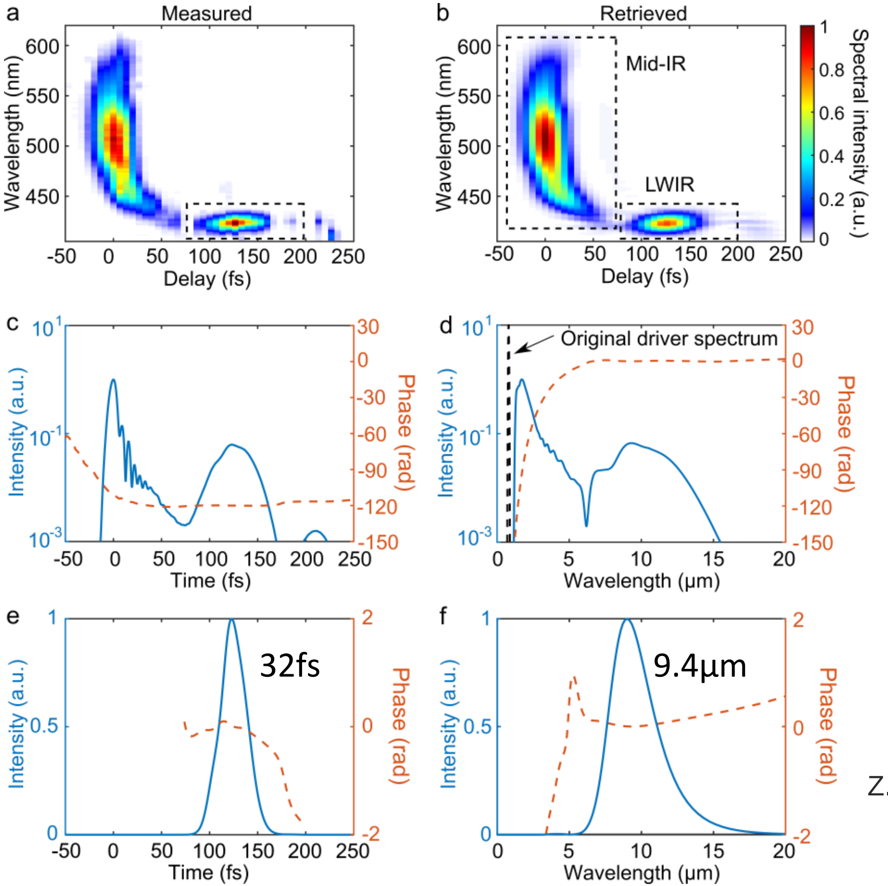
Retrieved IR pulse

UCLA

XFROG trace:

IR pulse:

LWIR portion
(in dashed box):



0.8 μm
36 fs
580 mJ

>0.6% →

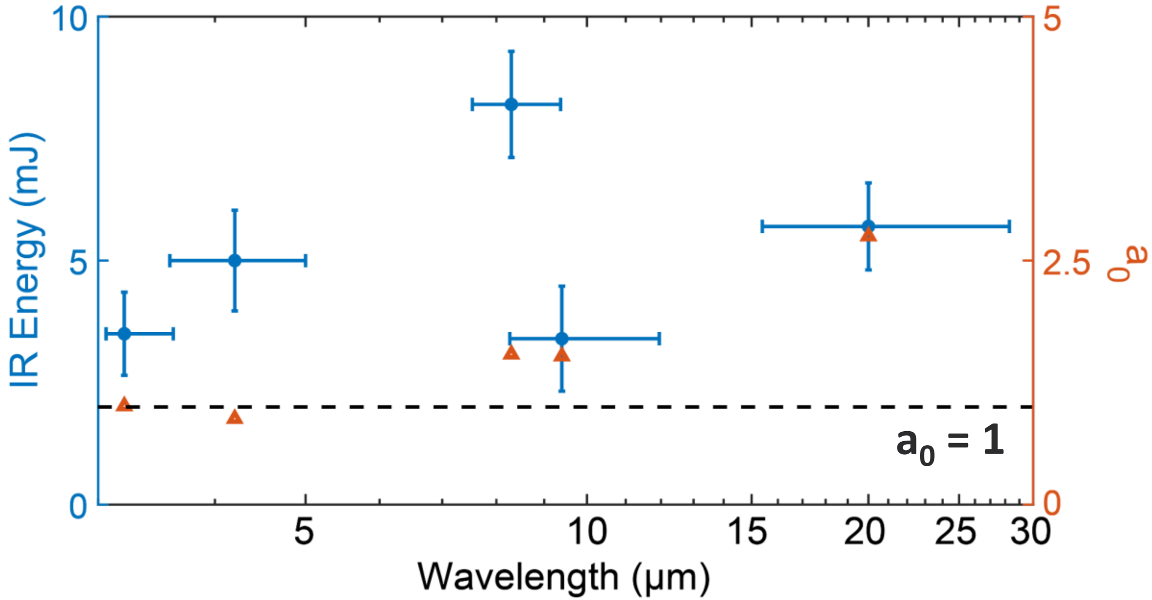
9.4 μm
32 fs
3.4 mJ

Z. Nie, et al. Nature Communications **11**, 2787 (2020)

Wavelength tunability (3-20 μm)

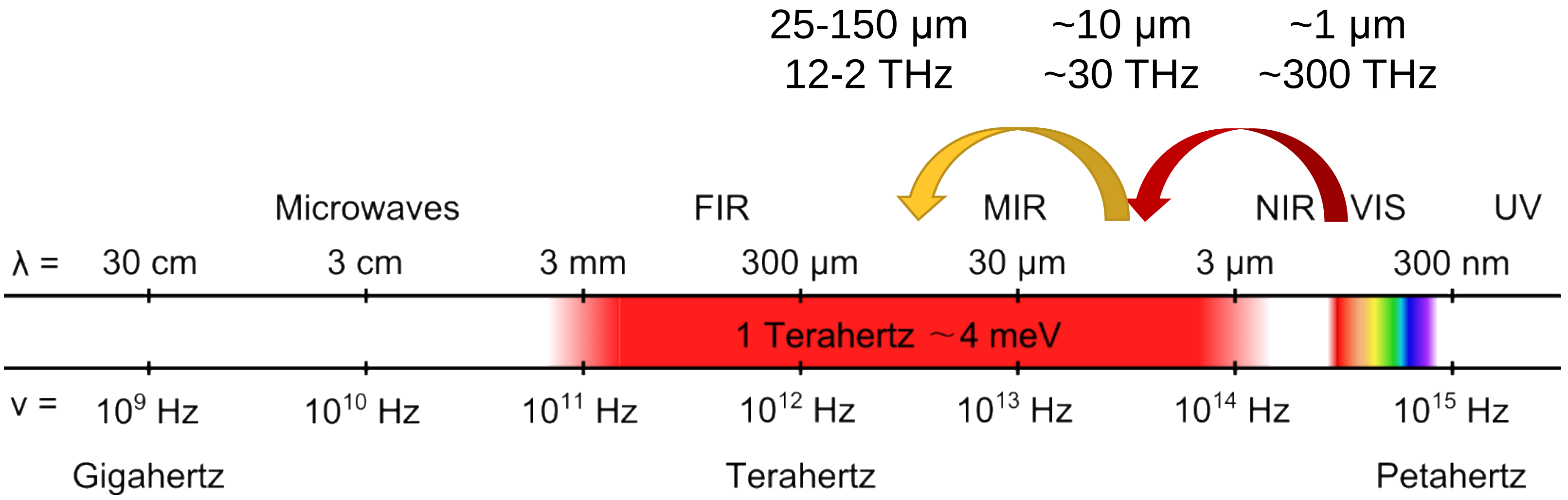
UCLA

- Varying plasma density profile and laser energy



THz pulses generated by CO_2 lasers

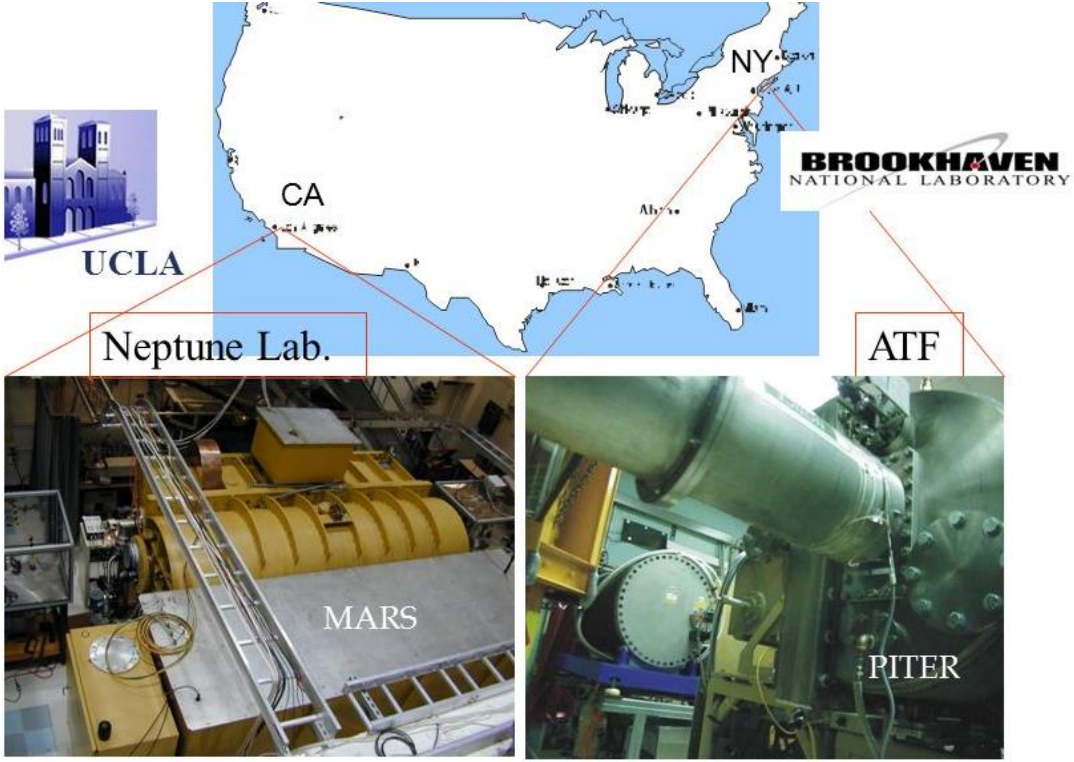
- Using the same scheme of photon deceleration
- Ti:sapphire laser → CO_2 laser



Picosecond TW CO_2 laser facilities

UCLA

15 TW, 3 ps



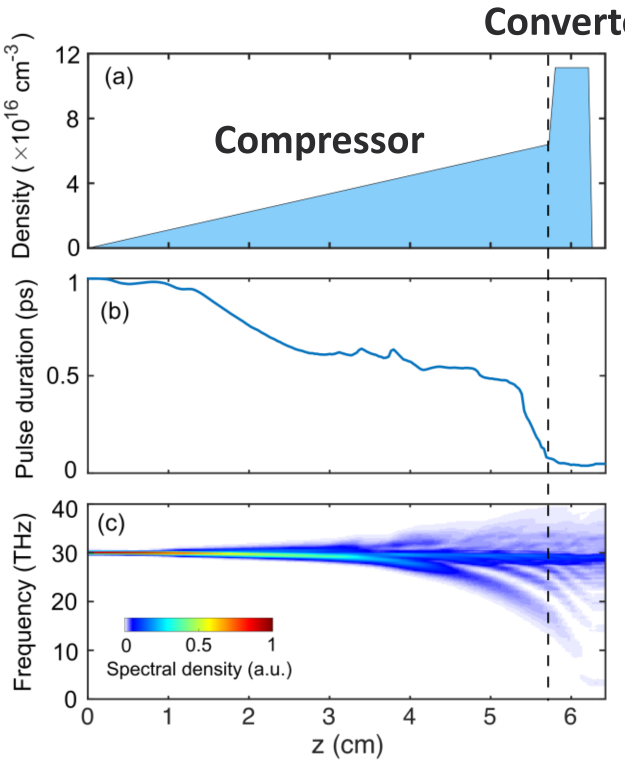
5 TW, 2 ps

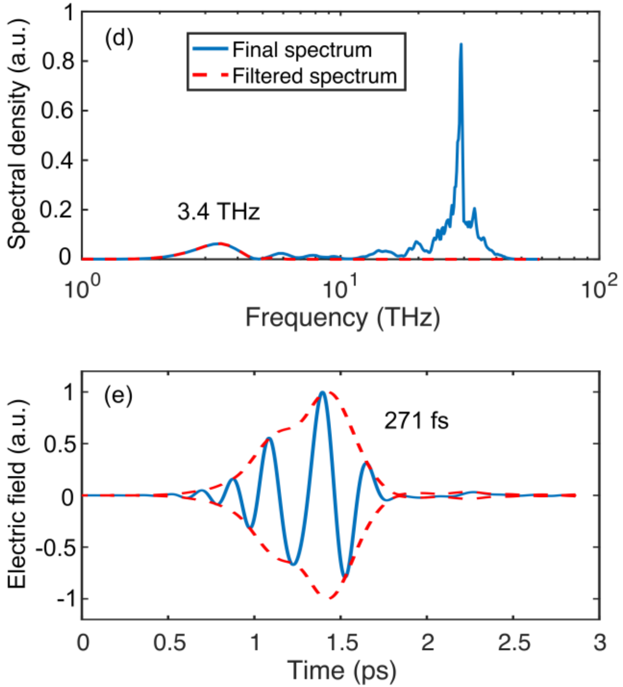
D. Haberberger, et al. Opt. Express, 18, 17865 (2010)

M. N. Polyanskiy, et al. Opt. Express, 19, 7717 (2011)

PIC simulations using OSIRIS quasi-3D code

UCLA





30 THz
1 ps
14.6 J

2%

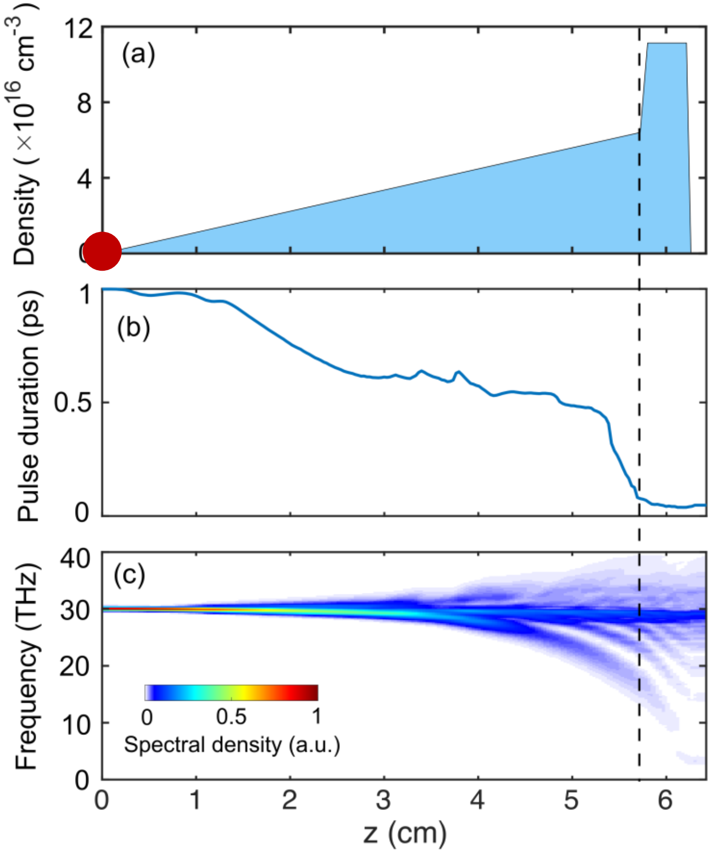
3.4 THz
271 fs
293 mJ

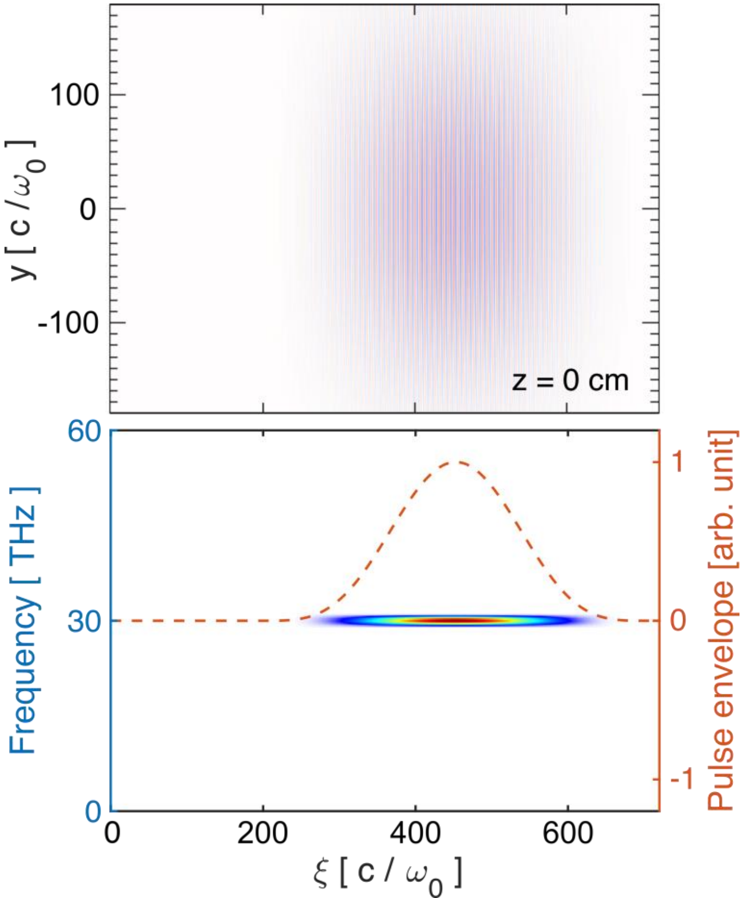
Peak power: 1.1 TW

Peak field: 2280 MV/cm

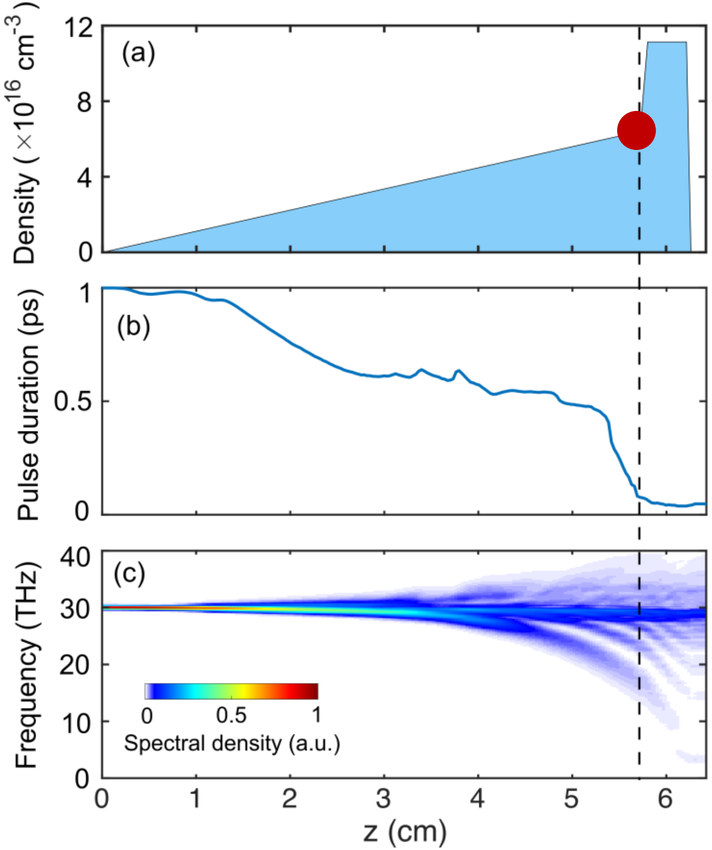
Z. Nie, et al. arXiv: 2012.00984

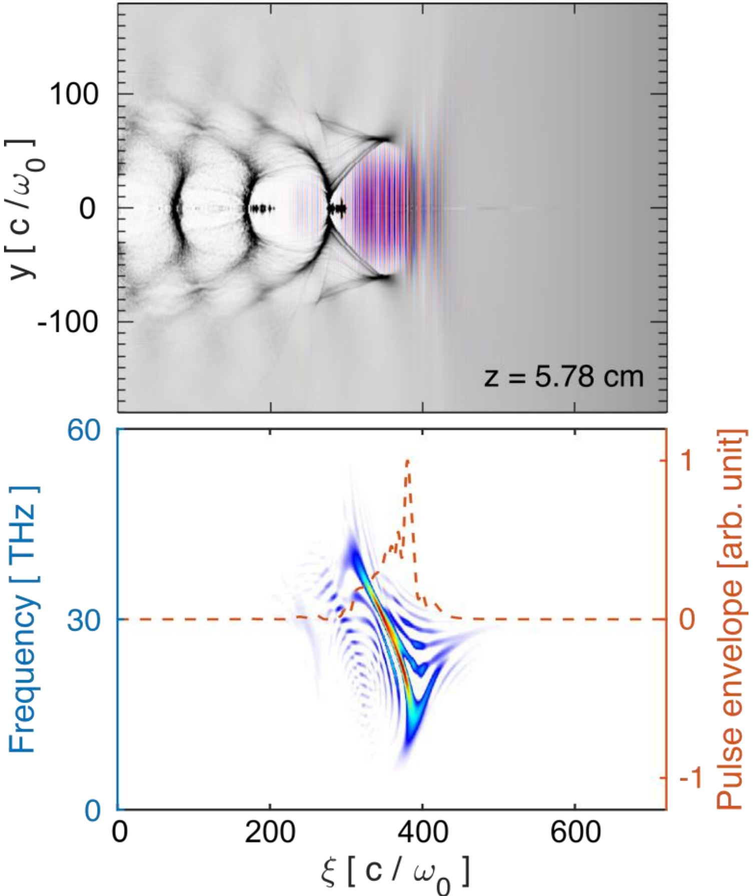
(1) At the beginning





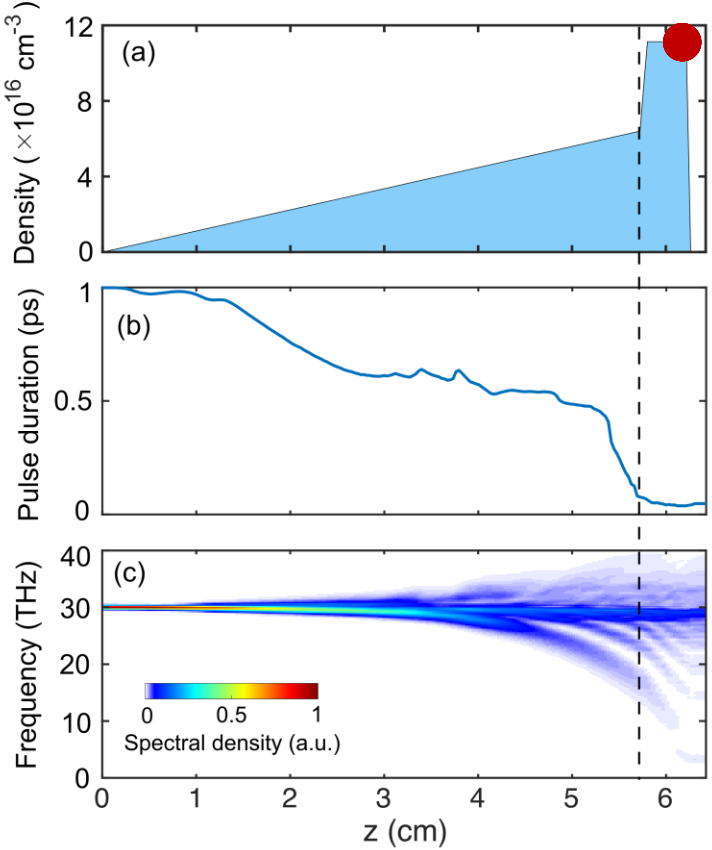
(2) Pulse compression

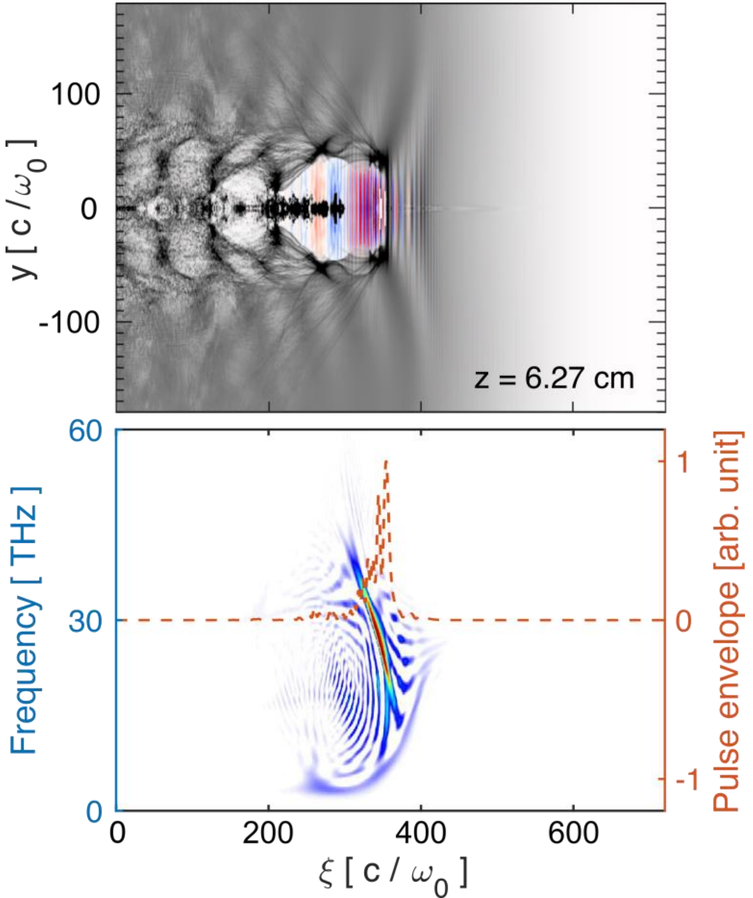




(3) THz generation

UCLA

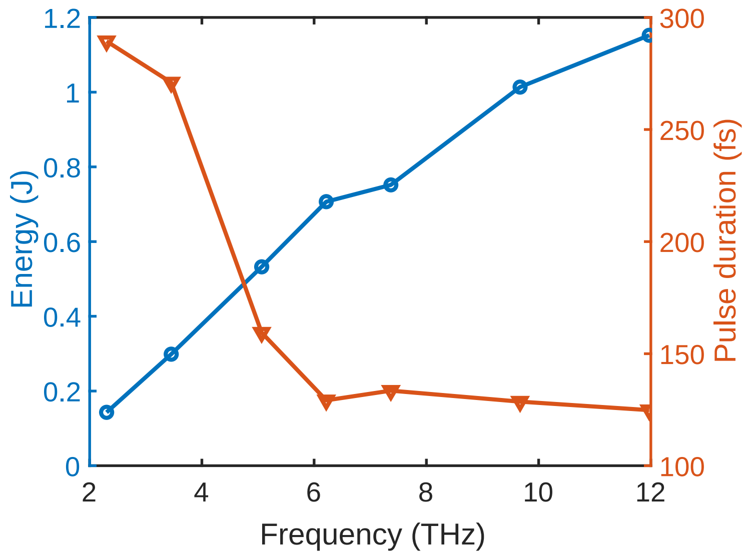


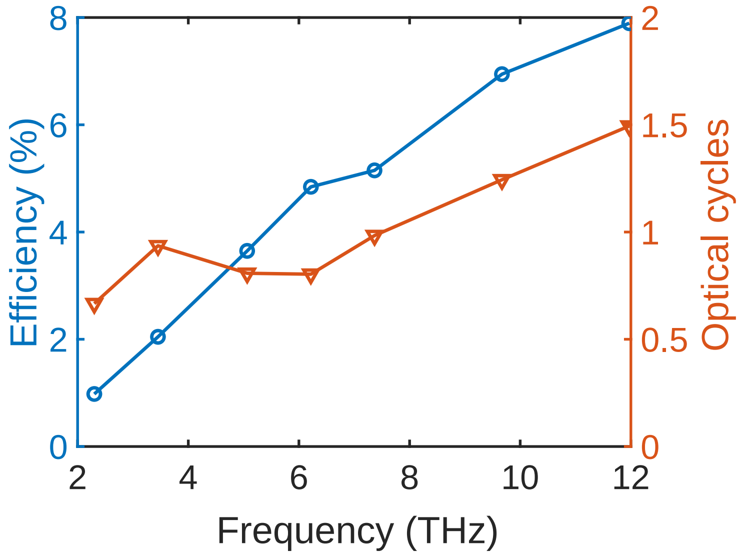


Frequency tunability (2-12 THz)

UCLA

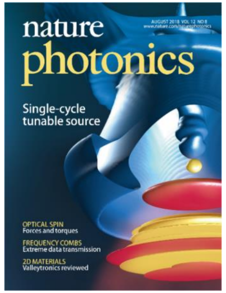
- Varying plasma density at converter section while keeping other parameters unchanged





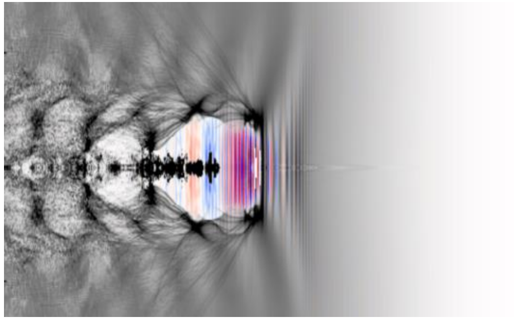
Summary

- Frequency downshifting in a tailored plasma structure was proposed and demonstrated to generate relativistic single-cycle infrared pulses tunable in the range of 3-20 μm.



- Extending this scheme to THz range (2-12 THz, or 25-150 μm) by using CO_2 drive lasers.

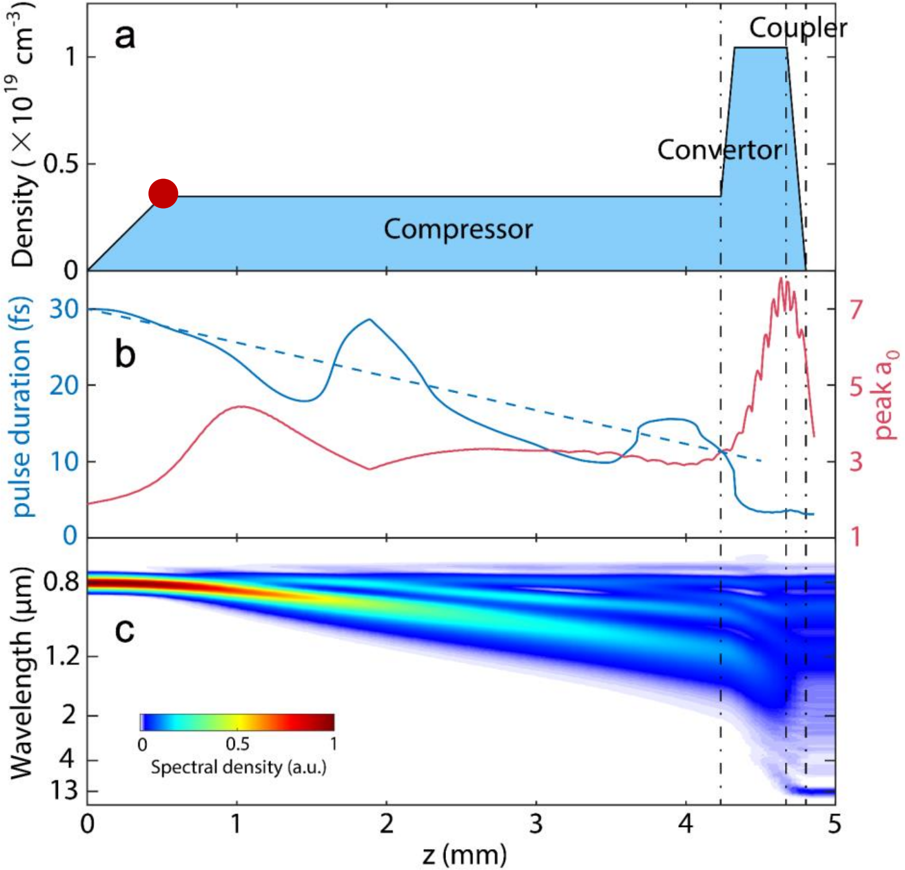
Thanks for your time!

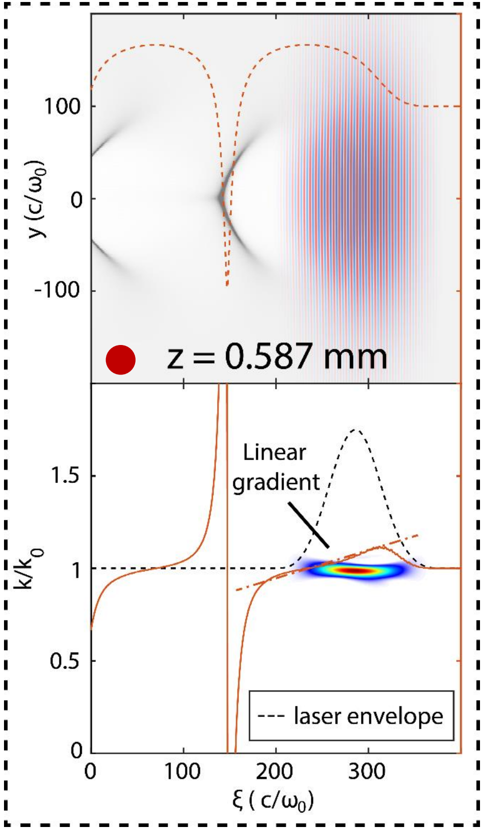


Back-up slides

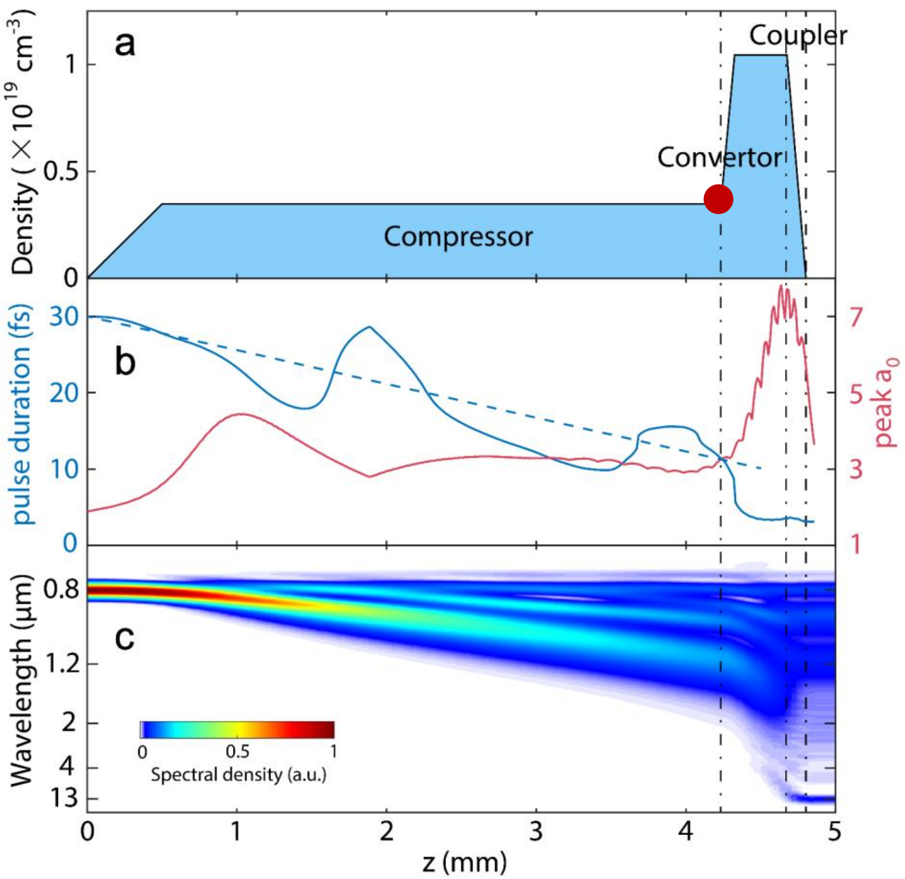
(1) At the beginning

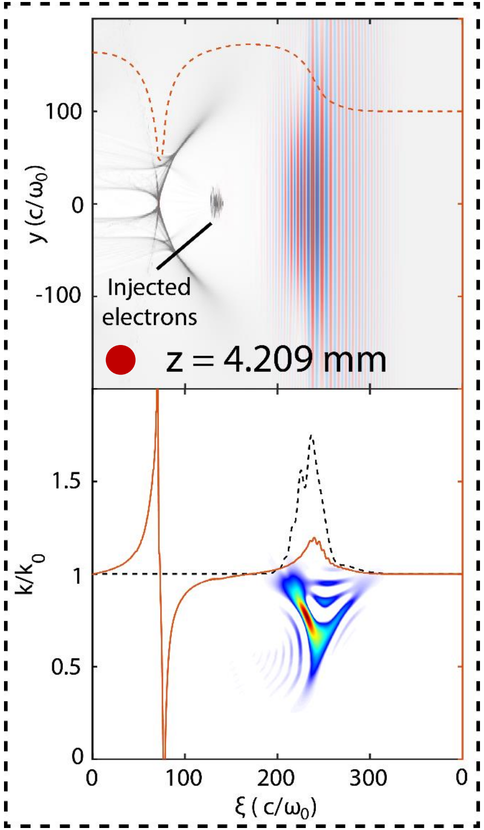
UCLA



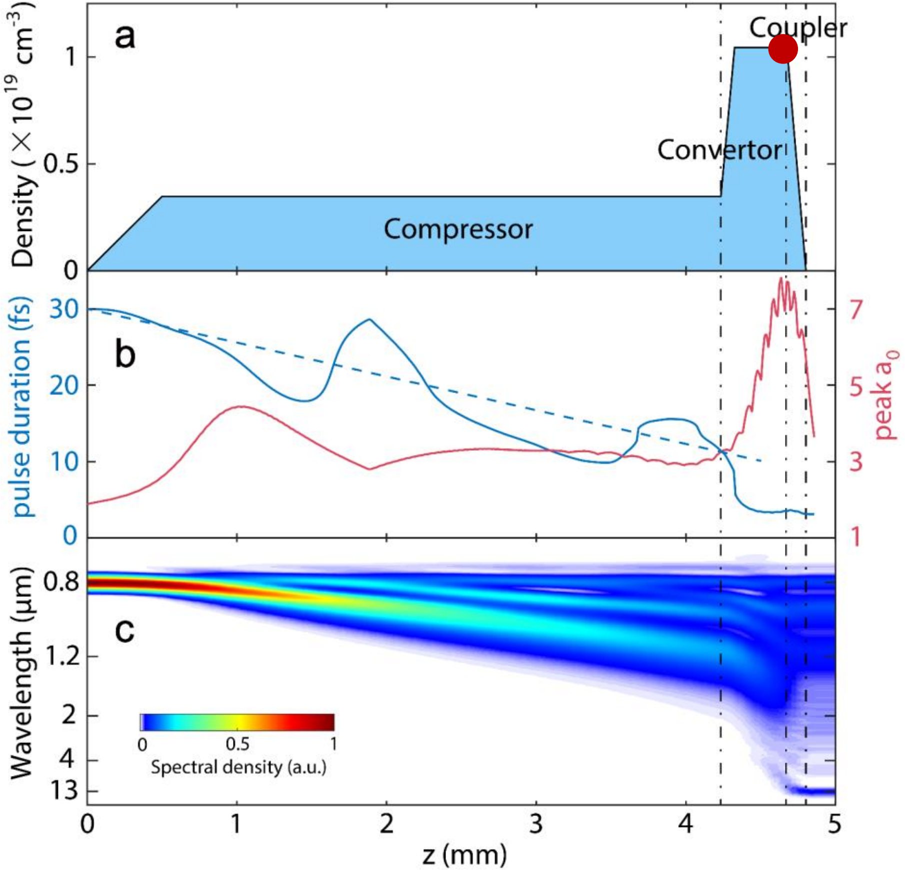


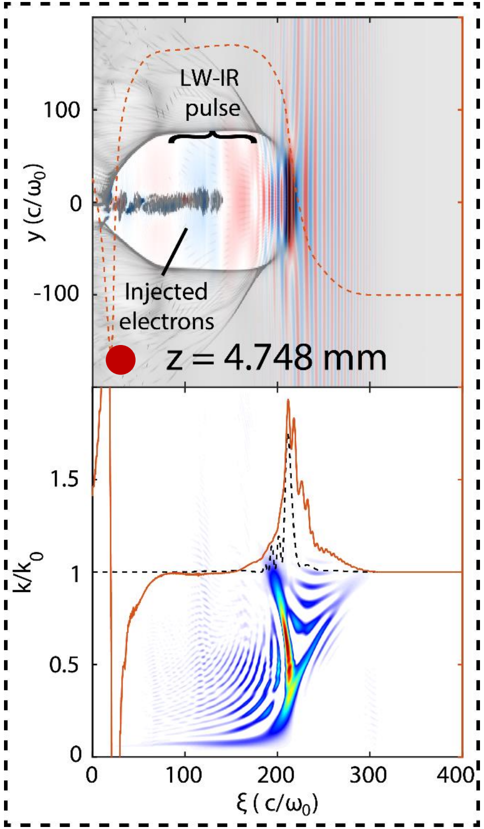
(2) Pulse compression



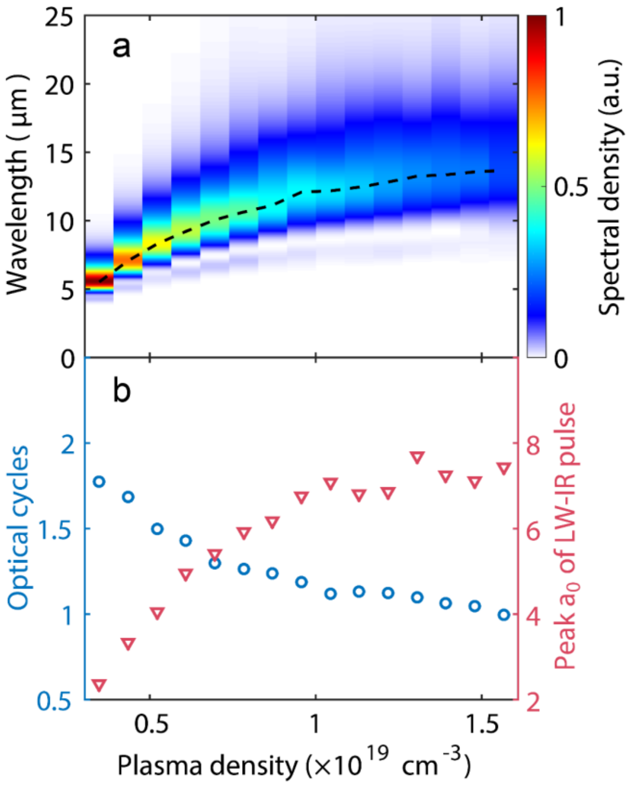


(3) LWIR generation





Wavelength tunability

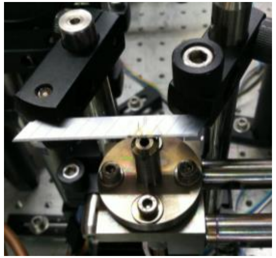


- Tunable from 5-14μm by varying plasma density and length in the converter
- Near-single-cycle in the whole parameter range

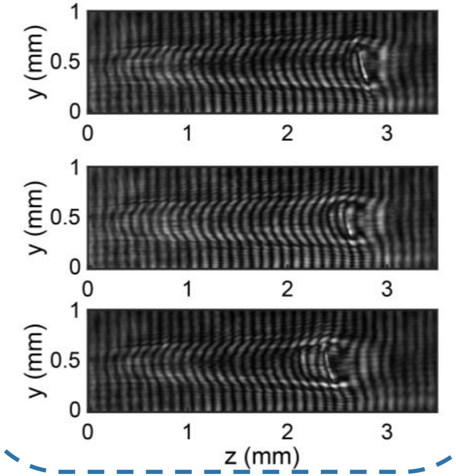
Plasma structure by blade-induced shock

UCLA

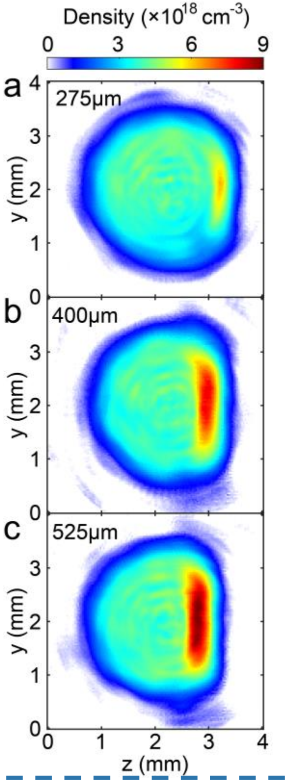
3mm gas jet with a blade

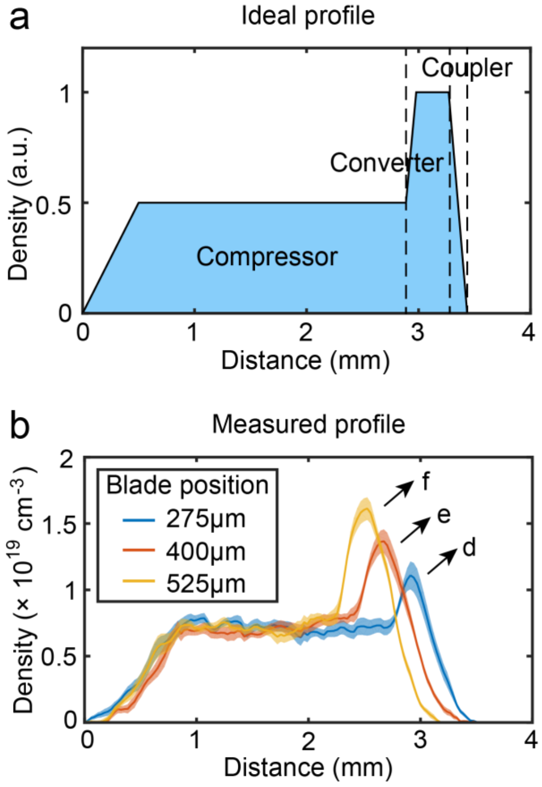


Online (Interferometry)



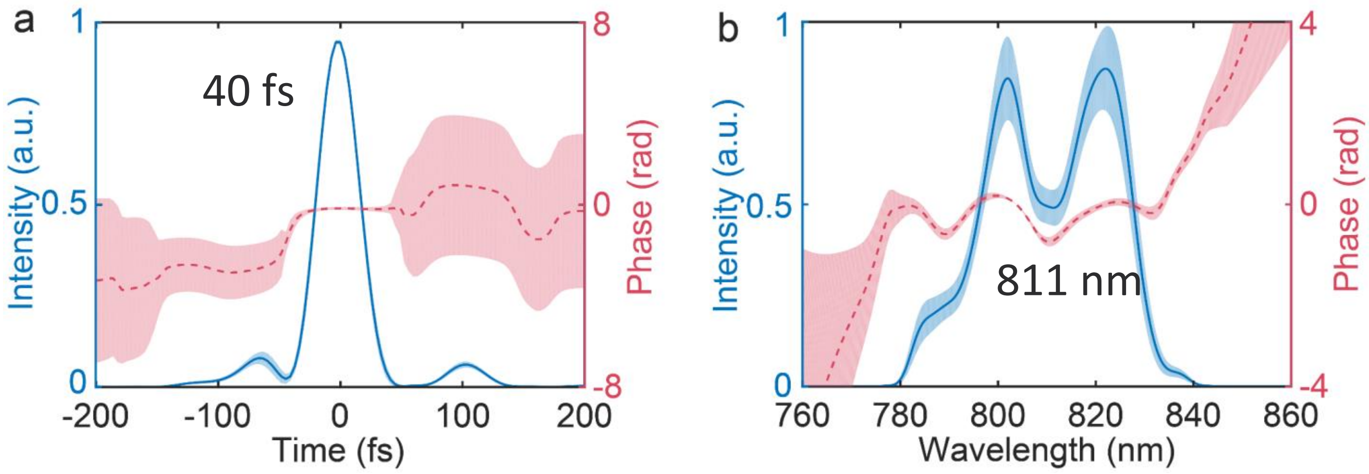
Offline (CT)



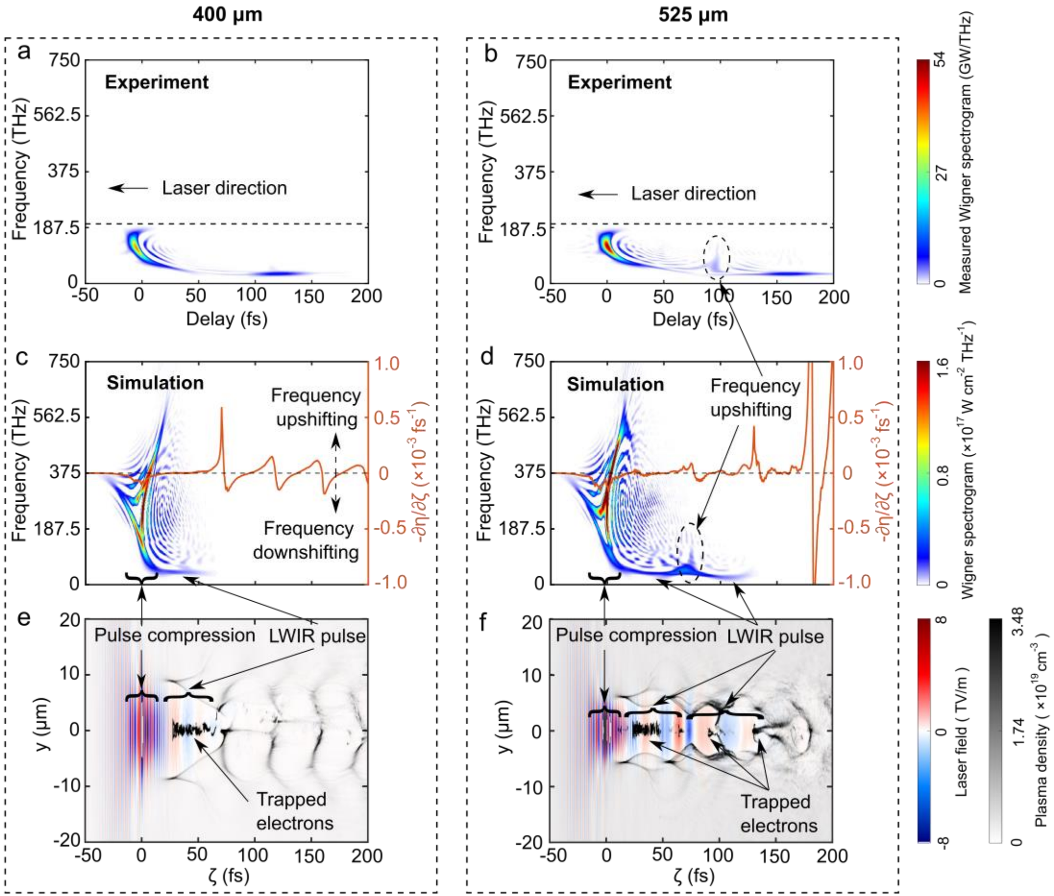


Reference pulse measured by Wizzler

- Statistical results of 60 shots



Diagnostics of wakes

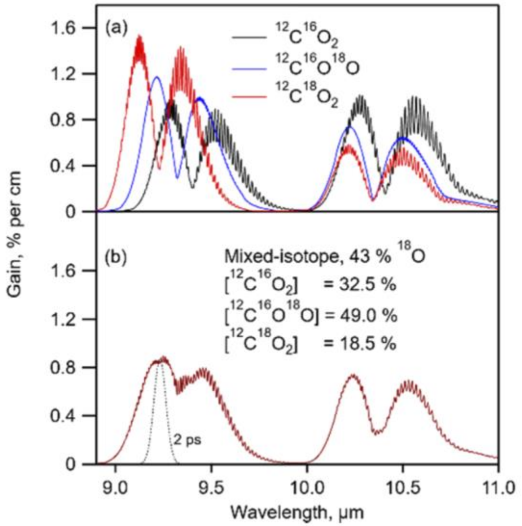


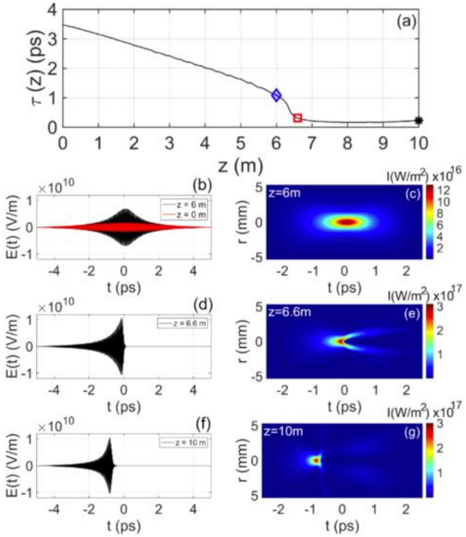
Towards sub-picosecond CO_2 pulses

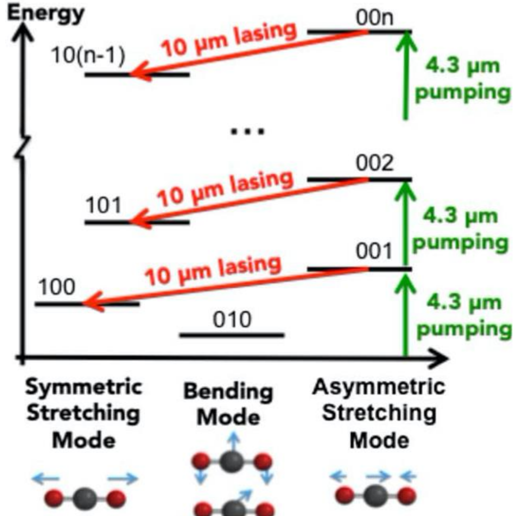
- BNL-ATF:
  - Using mixed-isotope CO_2

- UCLA-Neptune:
  - optical pumping using 4.3 μm lasers

- Self-compression to ~300 fs in a CO_2 cell







M. N. Polyanskiy, et al. OSA Continuum, 3, 459-472 (2020); P. Panagiotopoulos, et al. OSA Continuum, 3, 30403047 (2020); D. Tovey, et al. Appl. Opt. 58, 5756-5763 (2019)