



Recent progress of laser-driven particle/photon sources in the 100-TW laser facility at NCU

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WG4, Asian Forum for Accelerators and Detectors

Major collaboration



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清华大学
Tsinghua University

UCLA

Bo Guo, Jie Zhang, Yue Ma, Jianfei Hua and Wei Lu



Yipeng Wu, Zan Nie, Fei Li, Chaojie Zhang, Chan Joshi and Warren Mori

Yang Wan and Victor Malka

Outline

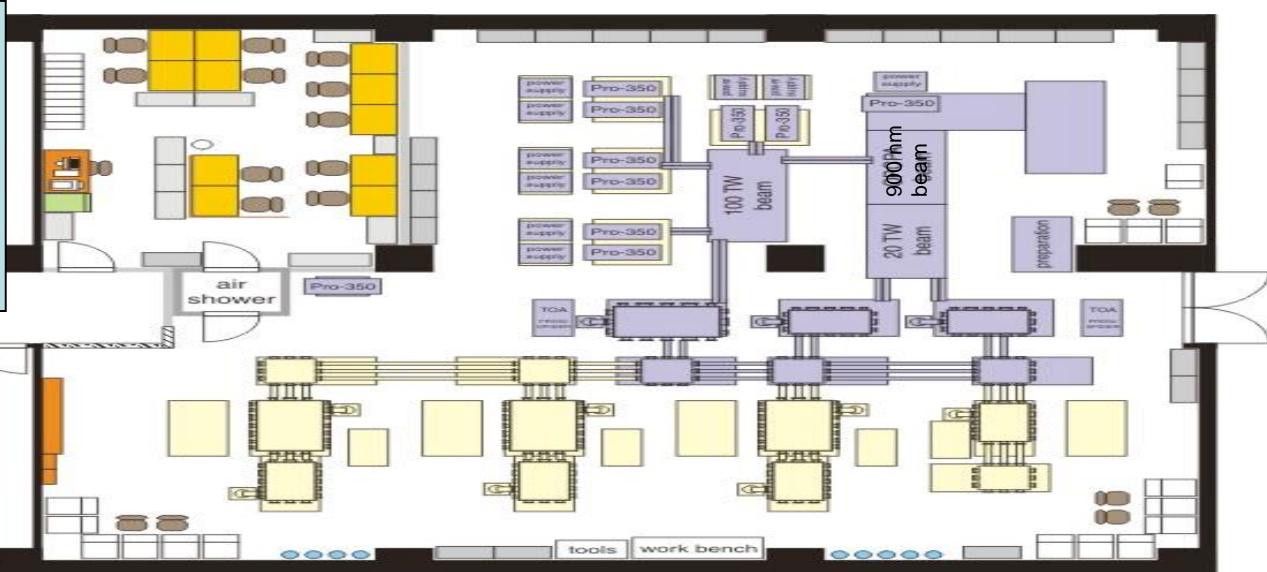
- **100-TW laser facility in NCU**
- **Laser-wakefield electron accelerators**
- **Laser-driven betatron x-ray sources**
- **Single-cycle intense mid-infrared pulses generated by laser-plasma interaction**

NCU 100-TW Multi-Beam Laser Facility (led by Prof. Wang)



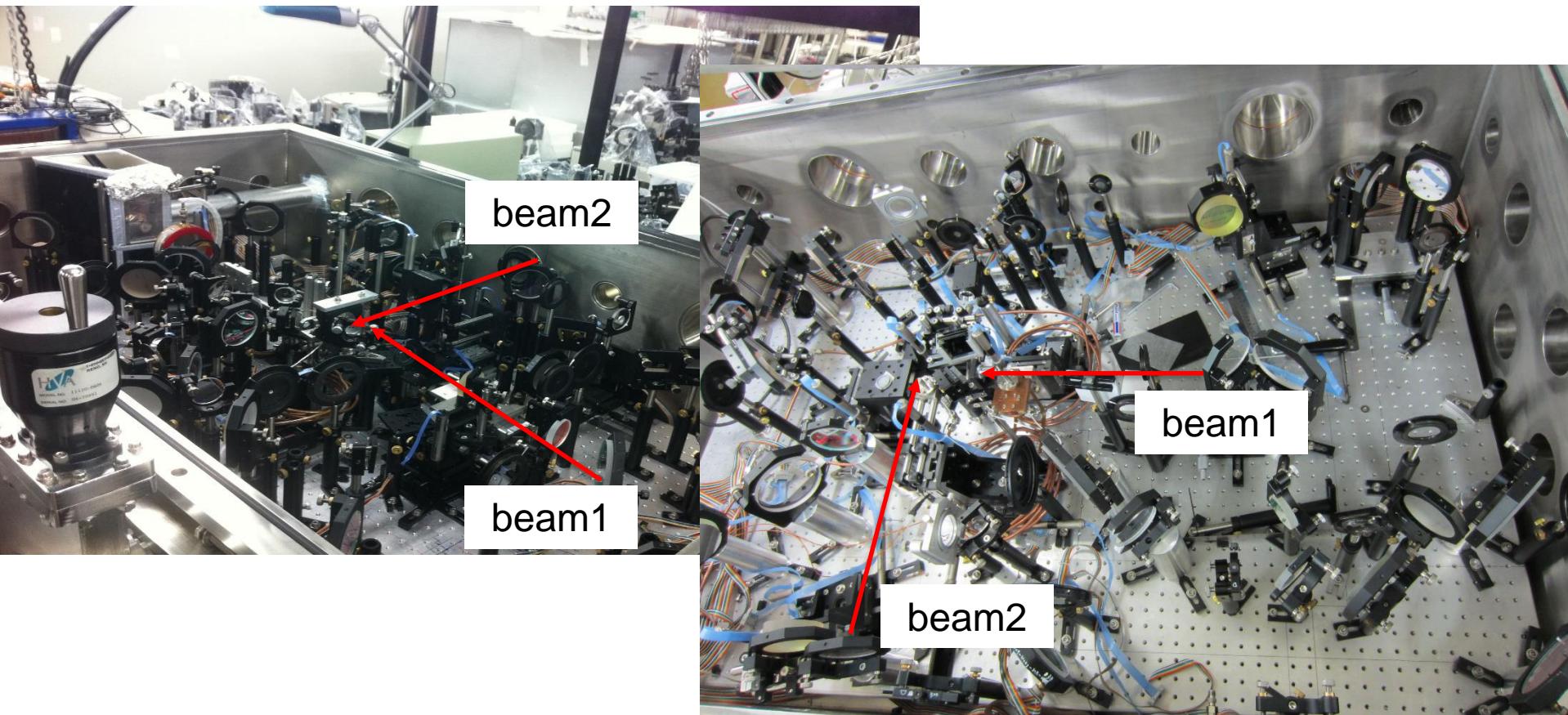
Multi-beam laser system:

1. 3.3-J, 30 fs, 810-nm
2. 0.45 J, 34 fs, 805-nm
3. 0.2 J, 38 fs, 870–920 nm tunable



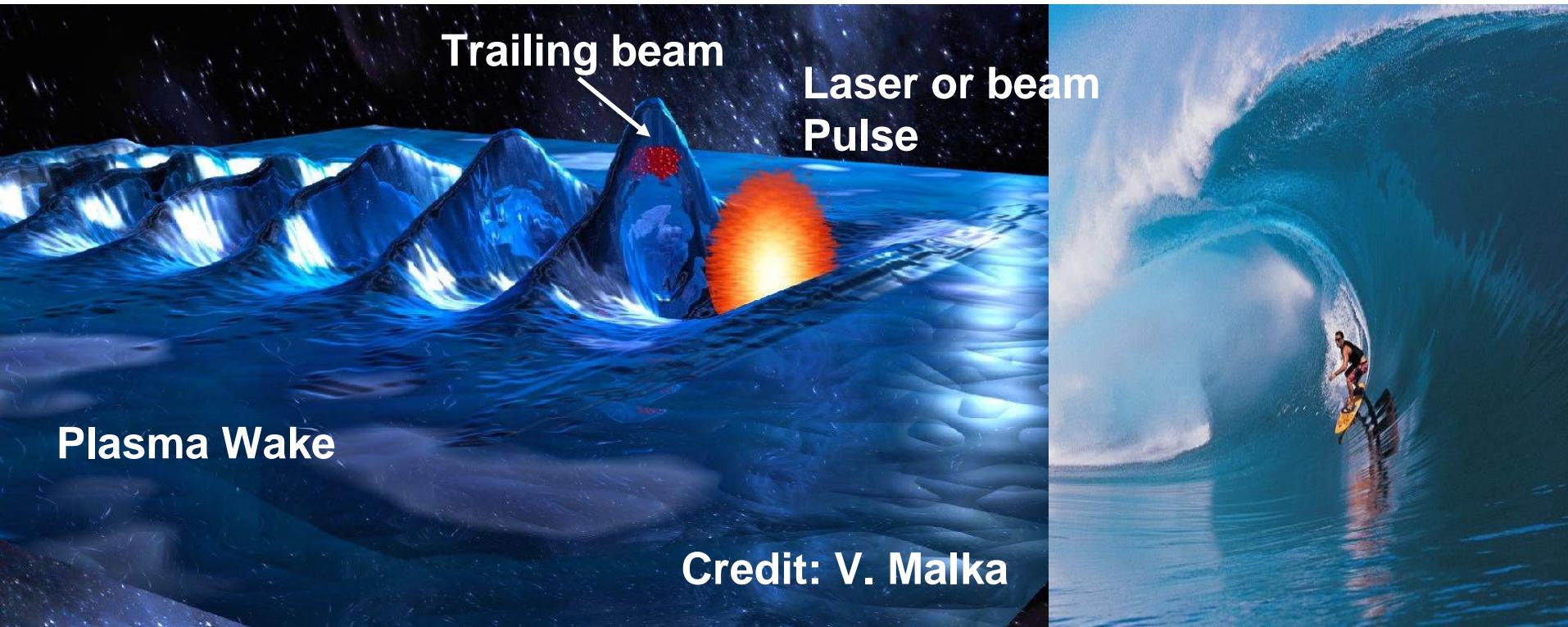
NCU/Tsinghua/UCLA Joint Platform for Laser-Plasma Interaction

Chamber 2 for ultrafast photon sources development



Chamber 3 for key physics study of LWFA

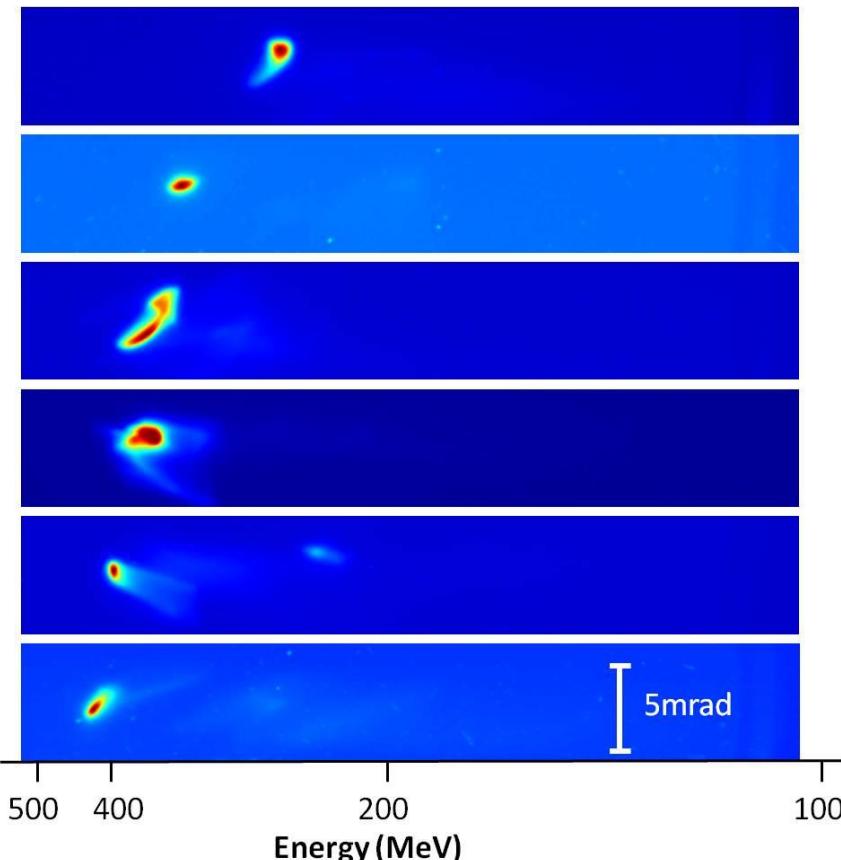
Light speed surfing on plasma wakes



Huge gradient (~100 GV/m) + Tiny structures (~10-100 μm)

T. Tajima and J. M. Dawson PRL (1979) [LWFA](#)
P. Chen, J. M. Dawson et.al. PRL (1983) [PWFA](#)

300-430MeV low energy spread (2-5%) electron beams using a 36-fs 50-TW laser at NCU



Energy (MeV)	RMS energy spread	Charge (pC)	Divergence angle (mrad)
265	2.1%	4.9	1.3
334	2.3%	0.89	0.83
367	5.2%	3.4	1.0
377	5.5%	11	1.6
408	2.3%	2.3	1.0
435	3.6%	0.96	1.6

$$\Delta E[\text{GeV}] \simeq 1.7 \left(\frac{P[\text{TW}]}{100} \right)^{1/3} \left(\frac{10^{18}}{n_p[\text{cm}^{-3}]} \right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu\text{m}]} \right)^{4/3} = 0.45$$

W. Lu et al., Phys. Rev. STAB 10, 061301 2007

Note:
the energy spread caused by beam angular spread has not been removed, therefore the real energy spread could be smaller!

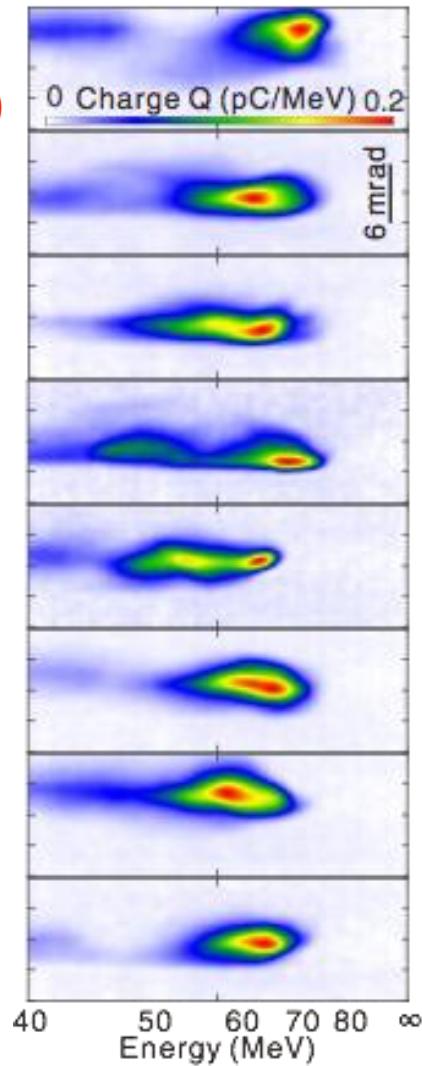
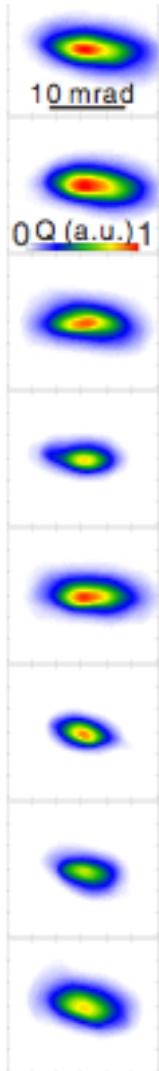
By C.H. Pai et al.,

Laser Parameters:
Pulse Energy: ~2J
Pulse Duration: 36fs
Laser Focal spot W_0 : ~27um
 $N_e = 5.6 \times 10^{18} \text{ cm}^{-3}$
4mm He jet

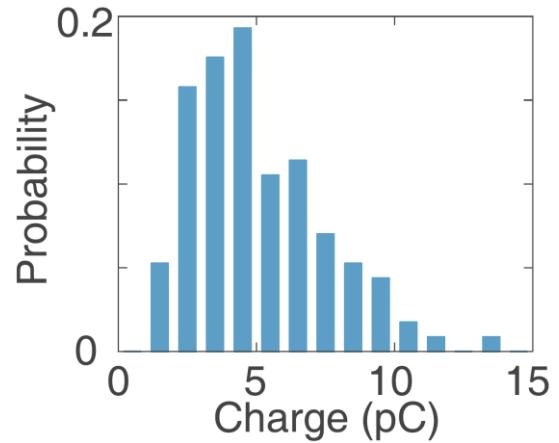
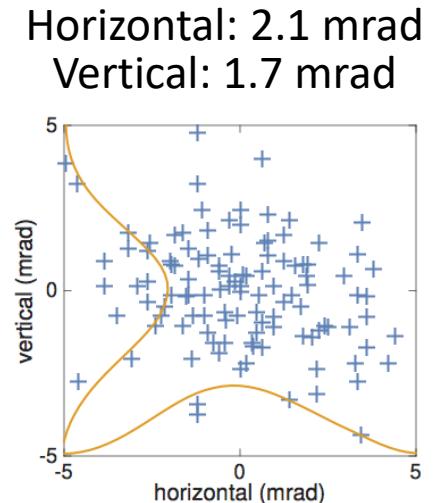
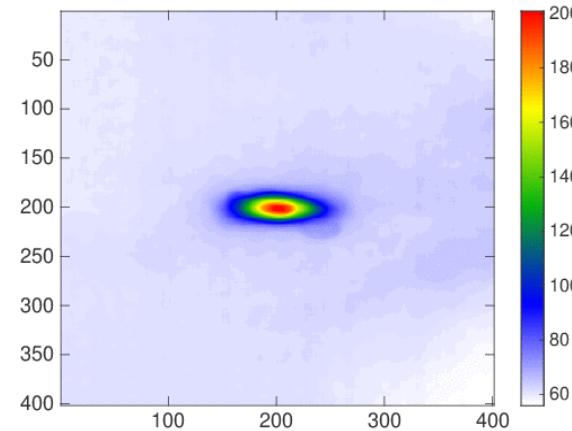
Generation of stable electron beams via ionization injection

Beam profile:

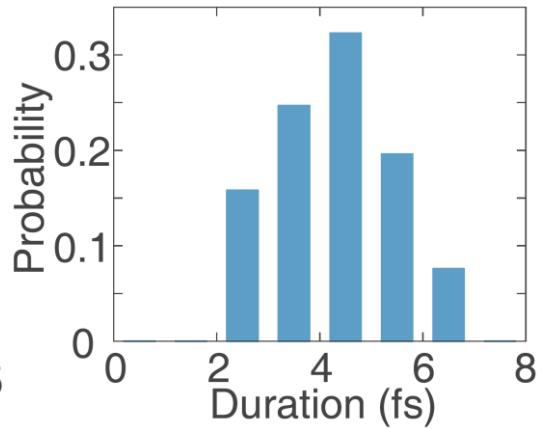
~300 μm (rms)
~3 mrad(FWHM)



Energy 60-80 MeV, $\Delta E/E \sim 20\%$



Charge: 2-10 pC



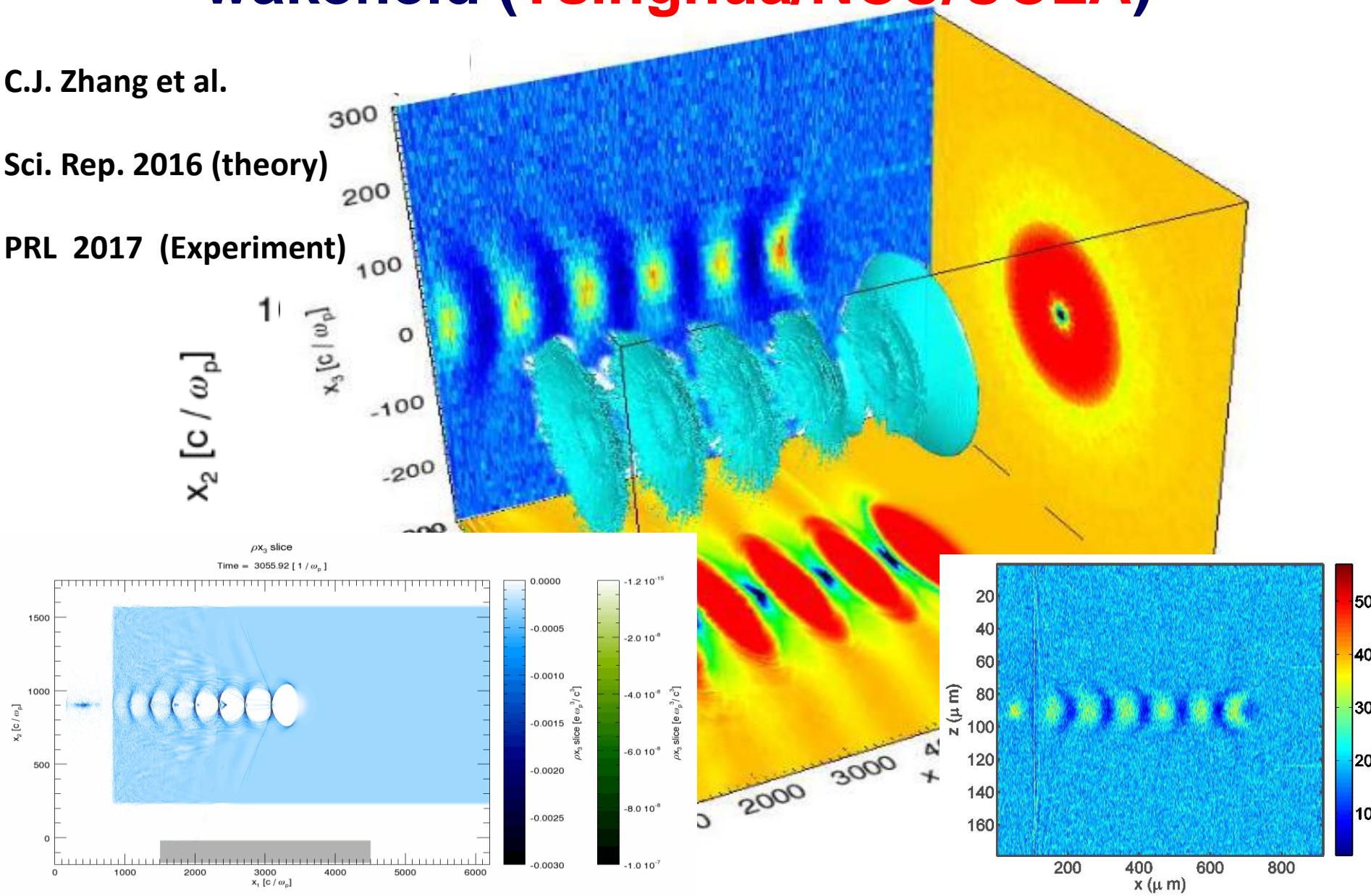
Duration: ~4.2 fs(FWHM)

Demonstration of electron snapshot of wakefield (Tsinghua/NCU/UCLA)

C.J. Zhang et al.

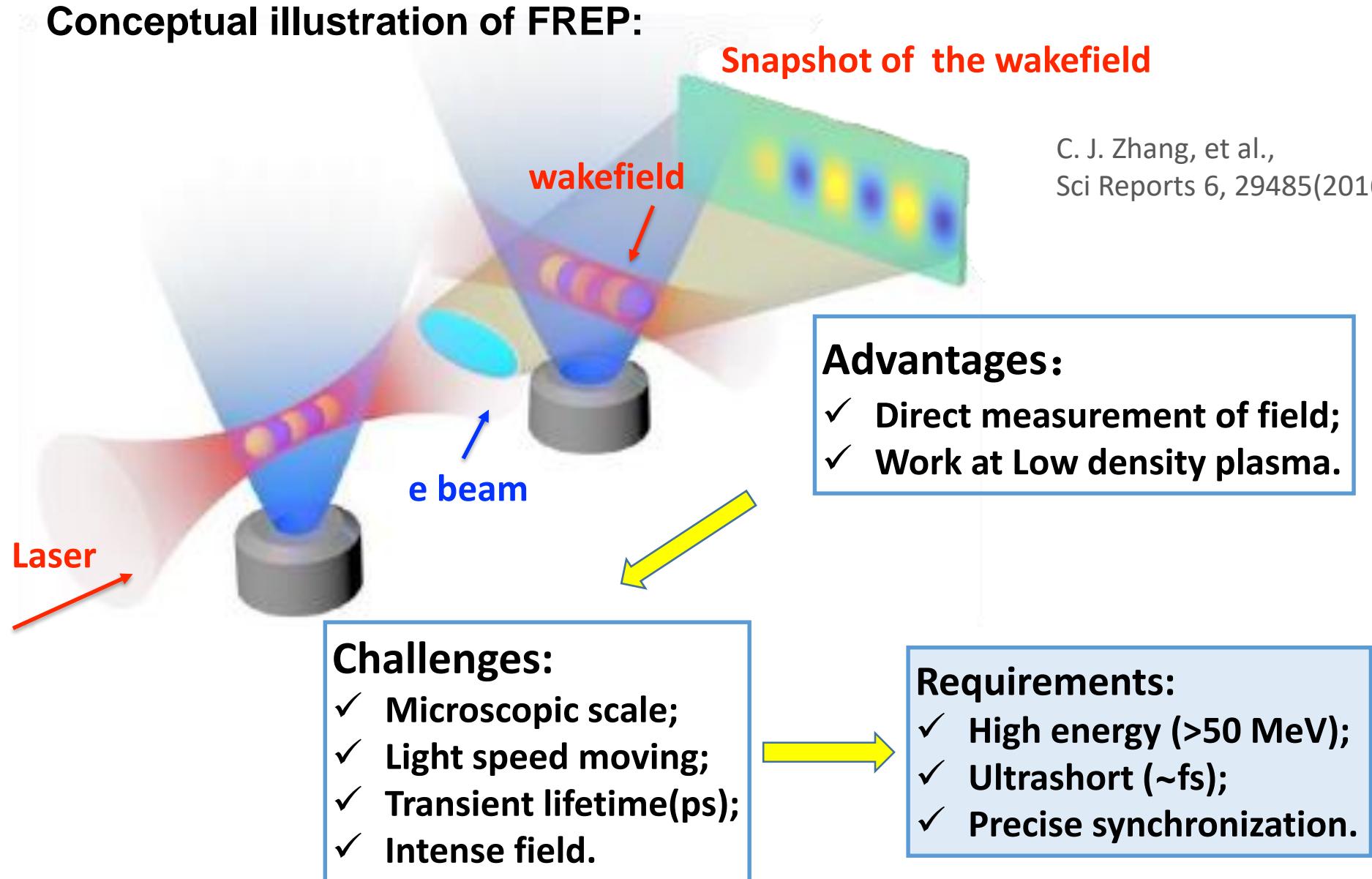
Sci. Rep. 2016 (theory)

PRL 2017 (Experiment)



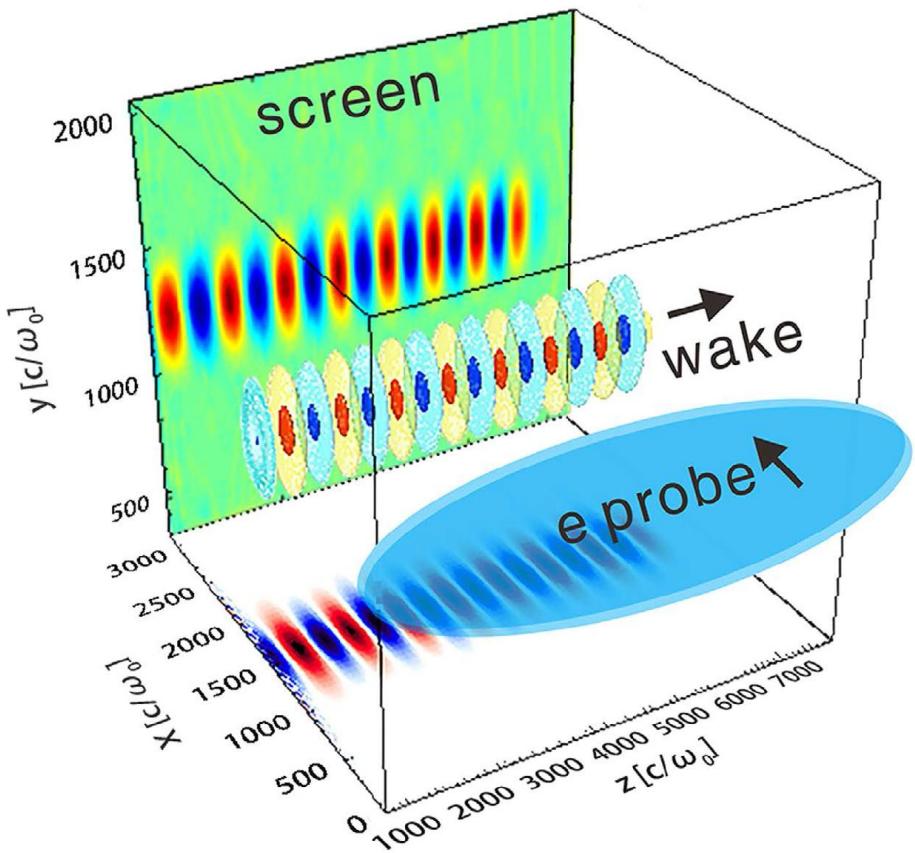
Femtosecond relativistic electron probe

Conceptual illustration of FREP:



C. J. Zhang, et al.,
Sci Reports 6, 29485(2016)

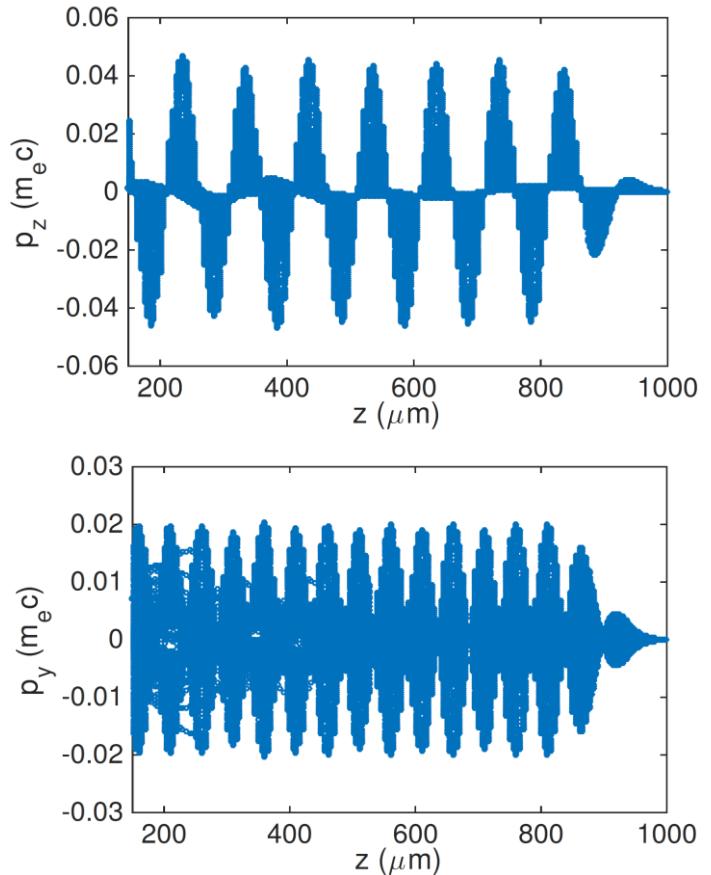
How does FREP work?



$$\frac{\partial I}{\partial z} = \kappa \nabla^2 \int_{-s}^s E_z(r, z - \beta_E x) dx$$

$$\frac{\partial I}{\partial y} = \kappa \nabla^2 \int_{-s}^s \frac{y}{r} E_r(r, z - \beta_E x) dx$$

Transverse momentum modulation

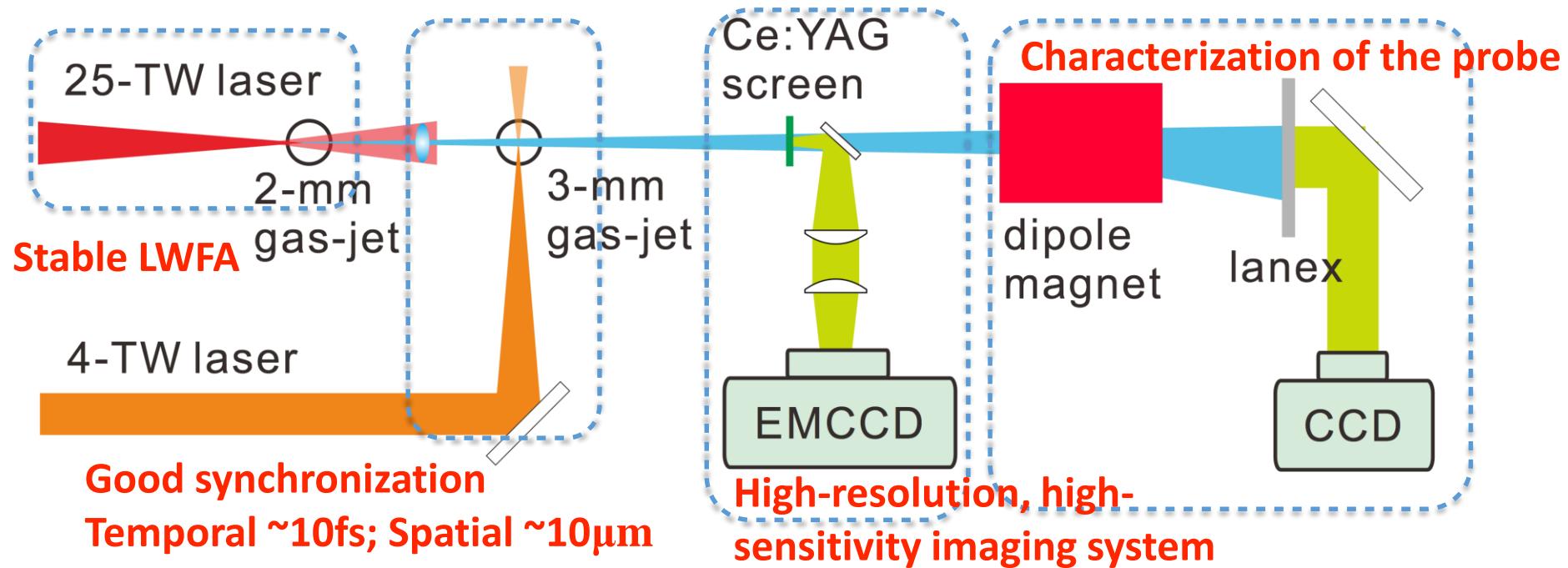


Density modulation: $I \equiv \delta n / n_0$

Experimental setup

100 TW laser platform at National Central University

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



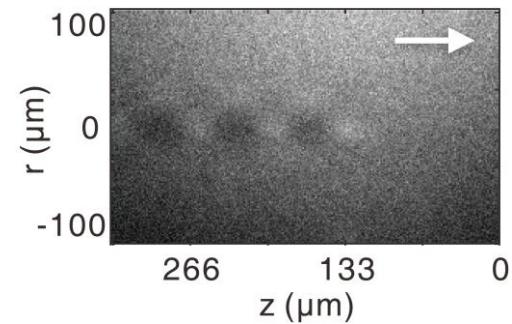
Quantitative reconstruction of the field structure

Theoretical model for wakefield reconstruction:

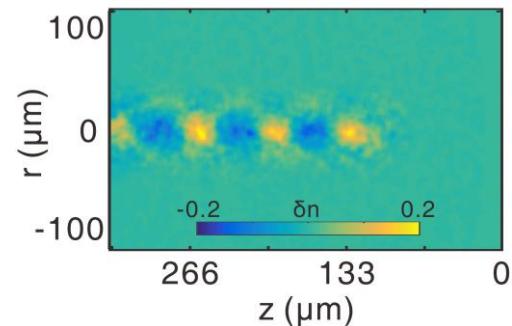
$$\frac{\partial I}{\partial z} = \kappa \nabla^2 \int_{-s}^s E_z(r, z - \beta_E x) dx$$

$$\frac{\partial I}{\partial y} = \kappa \nabla^2 \int_{-s}^s \frac{y}{r} E_r(r, z - \beta_E x) dx$$

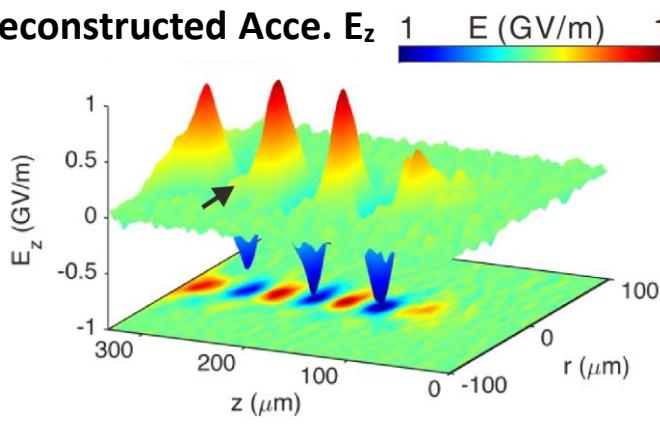
Raw data:



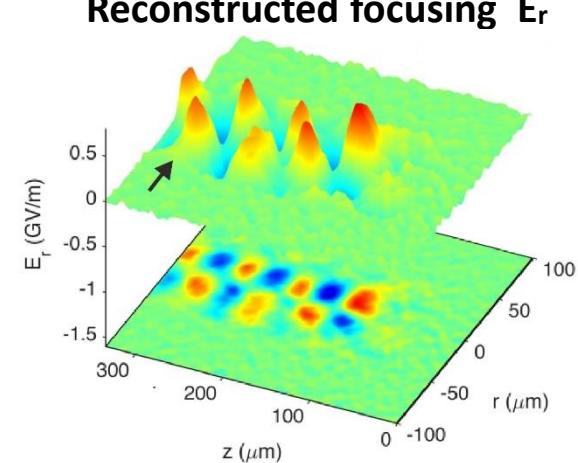
Density perturbation



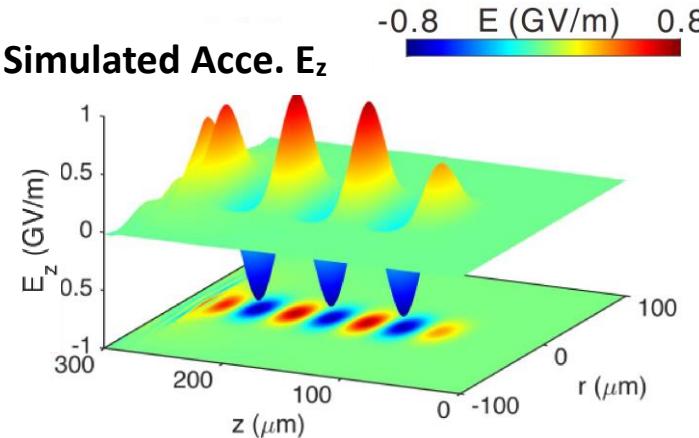
Reconstructed Acce. E_z



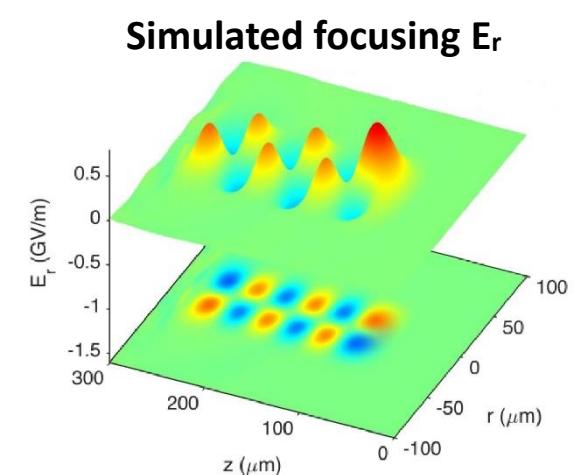
Reconstructed focusing E_r



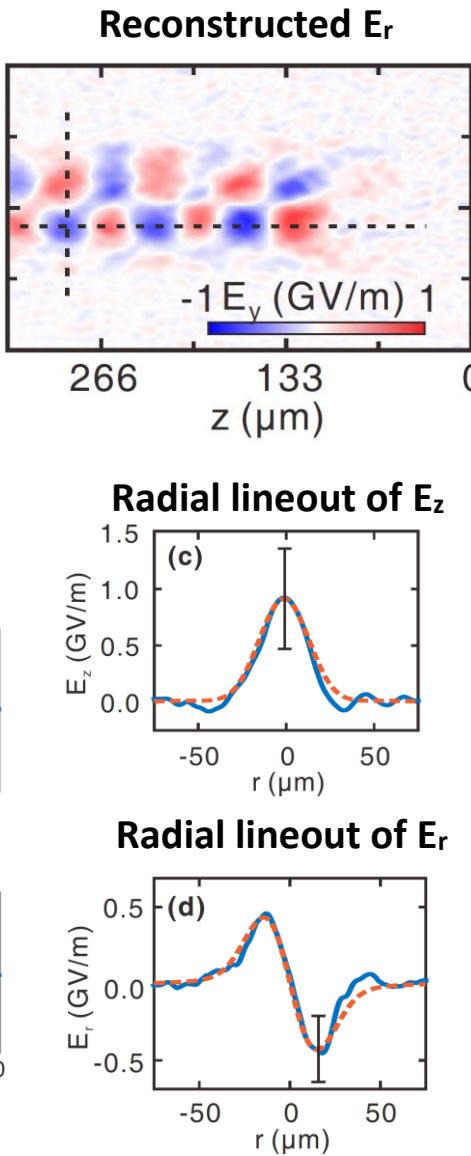
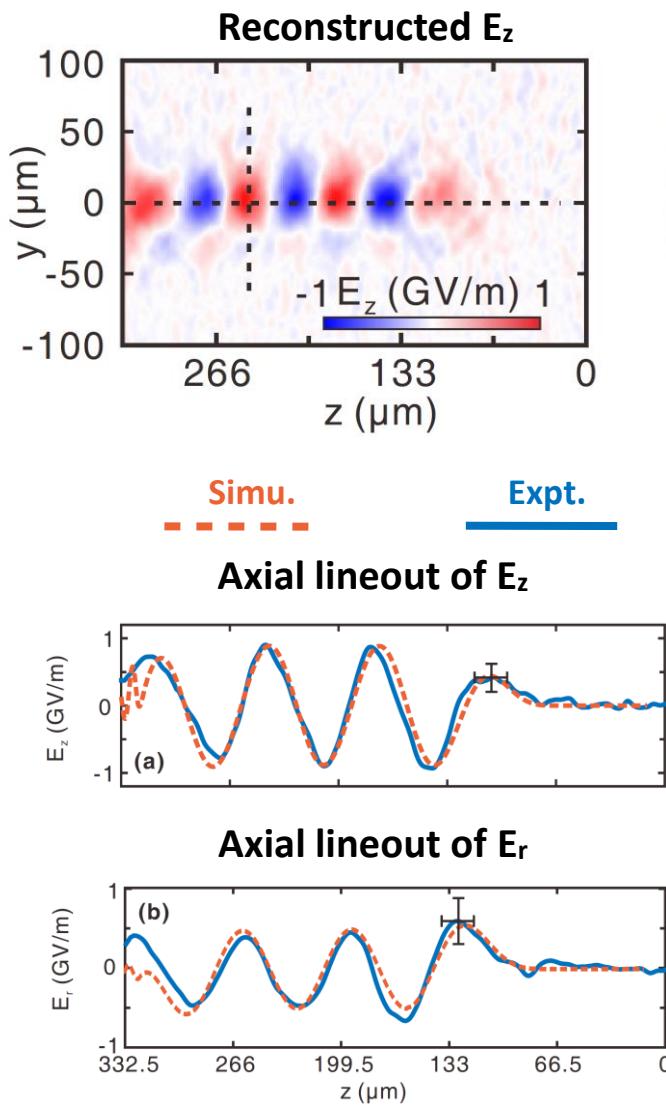
Simulated Acce. E_z



Simulated focusing E_r



Comparison between the experiment and simulation

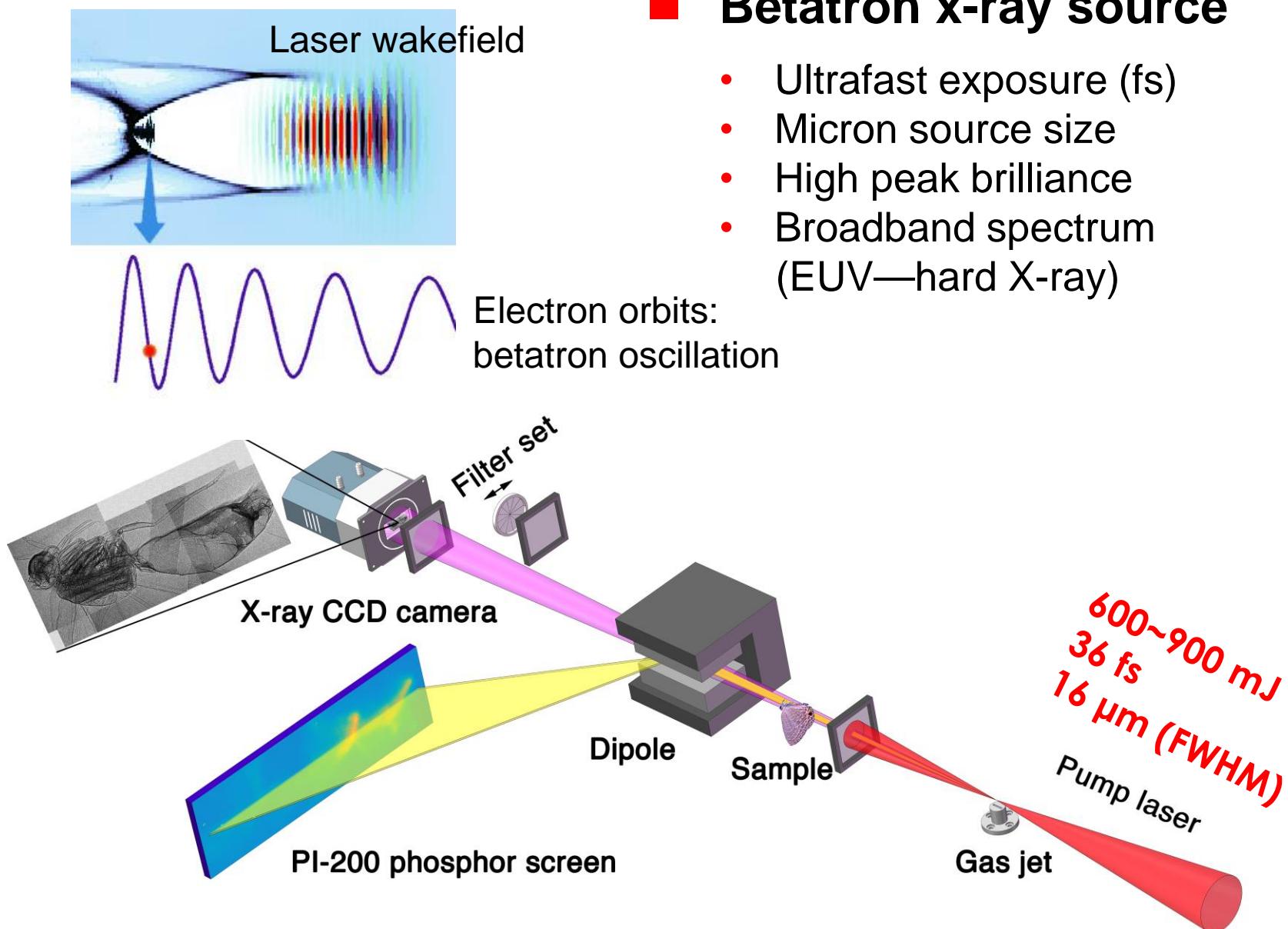


- ✓ E_z field: Sine form
- ✓ E_r field: $r^* \exp(-r^2/\sigma^2)$
- ✓ Peak E_z is ~ 1 GeV/m
- ✓ Linear E_r field (+/- 8 μm)

First measurement of the field structures in a plasma wake!

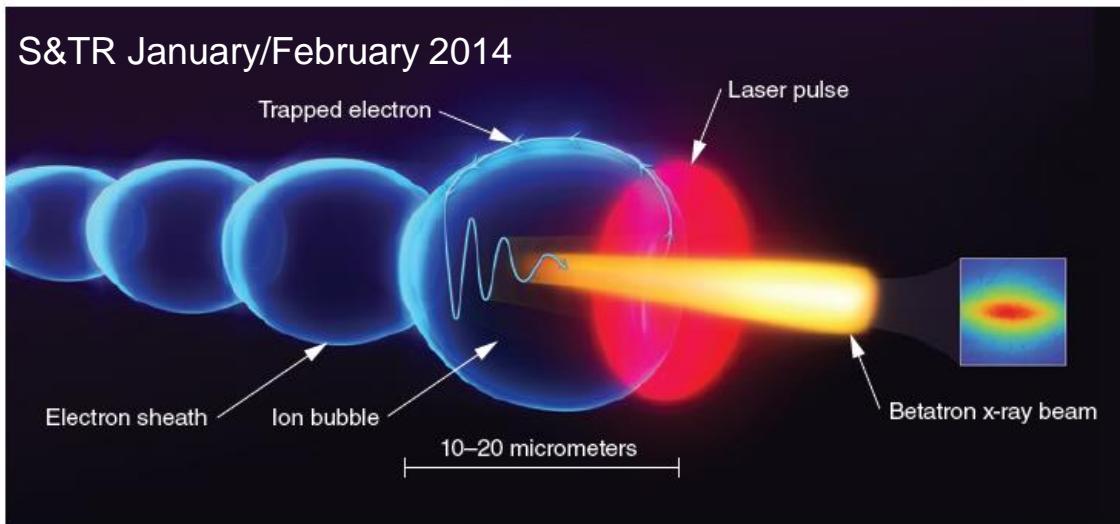
The technique also works for nonlinear wakes!

20-TW laser driven betatron X-ray source



20-TW laser-driven betatron x-ray source

S&TR January/February 2014

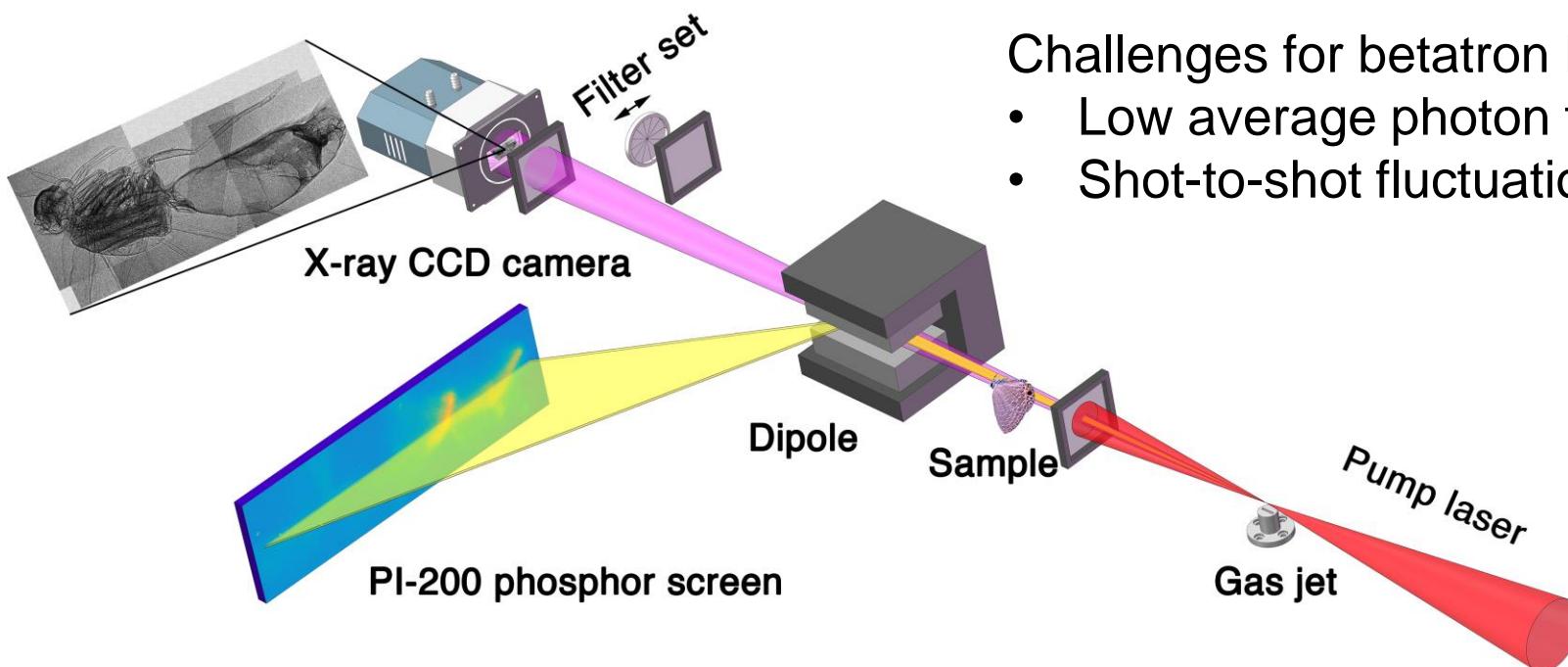


$$K = 1.33 \times 10^{-10} \sqrt{m_e [\text{cm}^{-3}]} r_\beta [\mu\text{m}]$$

$$\hbar\omega_c [\text{eV}] = 5.24 \times 10^{-21} \gamma^2 n_e [\text{cm}^{-3}] r_\beta [\mu\text{m}]$$

$$N_{\text{ph}} = 3.31 \times 10^{-2} N_e N_\beta K$$

S. Corde et al, Rev Mod Phys 85 (1), 1-48 (2013).



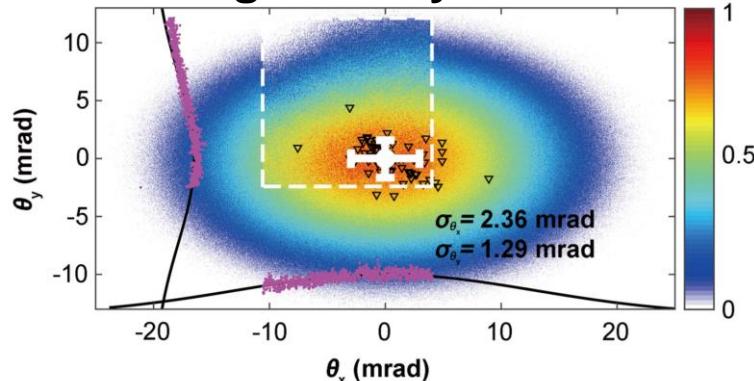
Challenges for betatron PCI:

- Low average photon flux
- Shot-to-shot fluctuations

More stable laser-driven x-ray sources

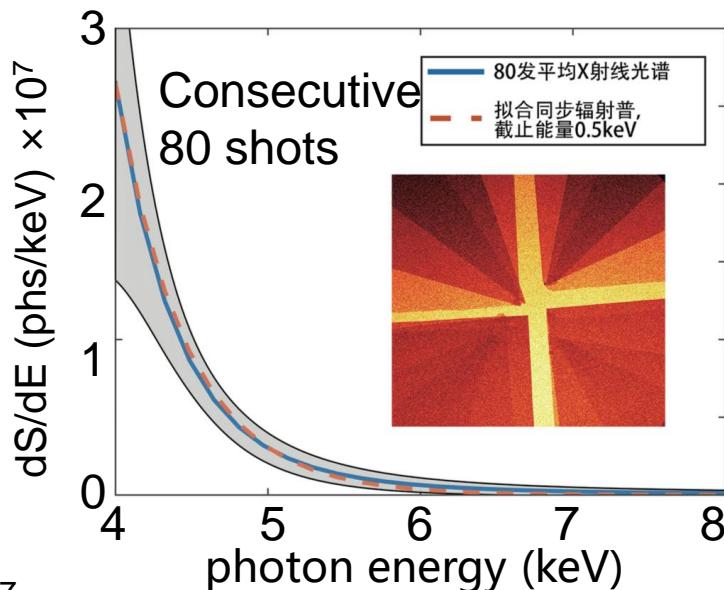
- Using 20 TW laser in NCU, via ionization injection, betatron x-ray sources can be generated with very stable pointing, spectrum, photon numbers for shot-to-shot.

■ Pointing stability

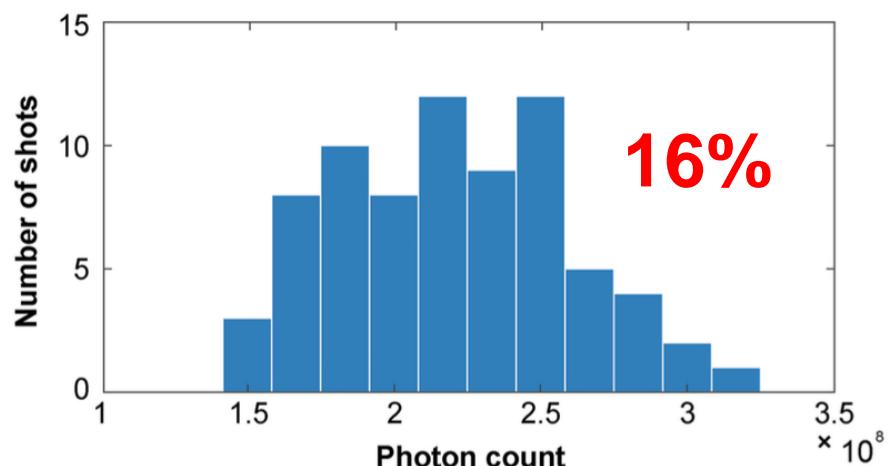


- Statistics of 80 shots
- Averaged divergence: $25.2 \times 17.2 \text{ mrad}^2$ (FWHM)
- Pointing jitter: $2.35 \times 1.29 \text{ mrad}^2$
(9.3% × 7.5%)

■ Stability of photon numbers and x-ray spectrum



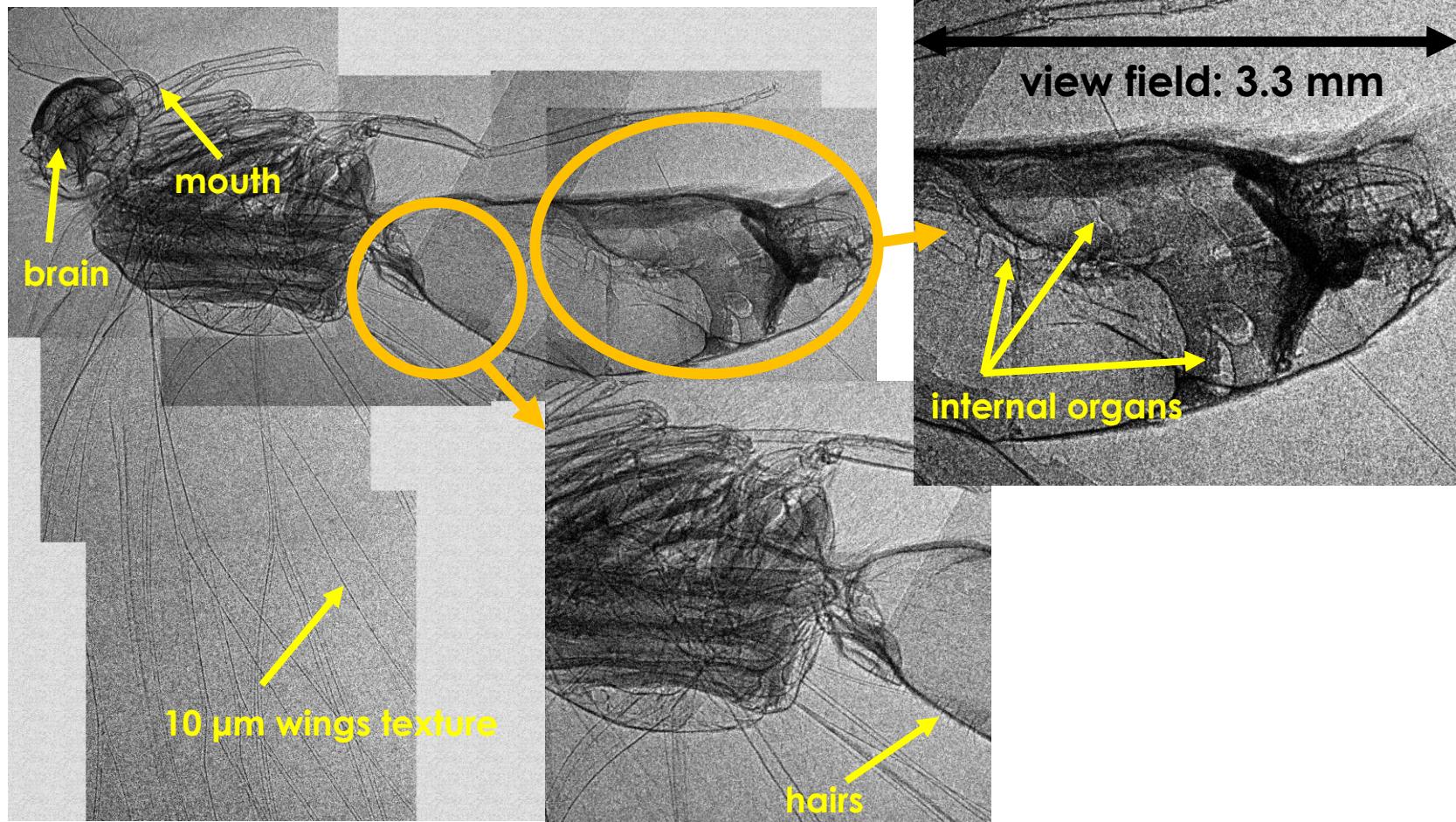
- Photon numbers: $(2.2 \pm 0.3) \times 10^8 \text{ phs/shot}$



Phase-contrast imaging of a butterfly

- ~1cm butterfly
(10 shots accumulation)

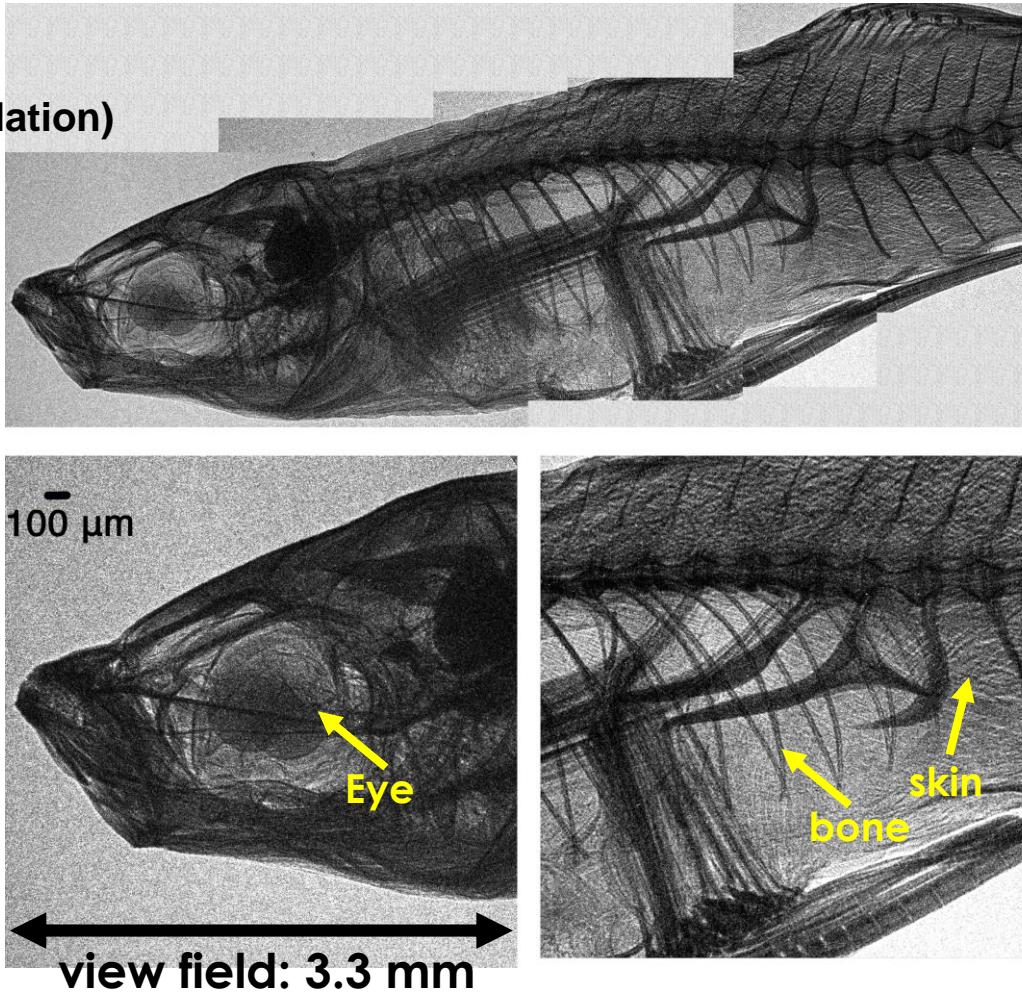
- The image resolution is about $5.5 \mu\text{m}$.
- The image contrast is at least 0.61 .



Phase-contrast imaging of a fish

Scientific Reports, 9, 7796 (2019)

- ~1cm fish
(20 shots accumulation)

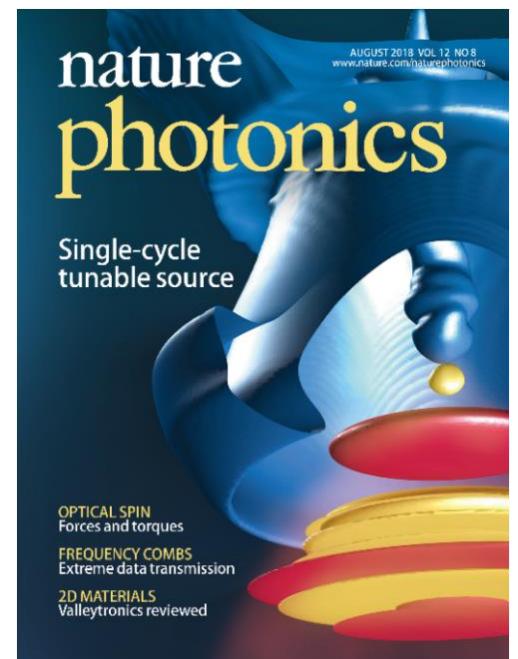


- In summary, this shows a way for applications of high resolution phase-contrast imaging with stable betatron sources using modest power, high repetition-rate lasers.

Tunable Relativistic, Single-Cycle Infrared Pulses from Laser-Plasma Interaction

Nature Photonics **12**, 489-494 (2018) (Simulation).

Nature Communications **11**, 2787 (2020) (Experiment).



Ultrashort infrared pulses

From near-infrared (NIR) to mid-infrared infrared

(0.8-1) μm



(2-20) μm

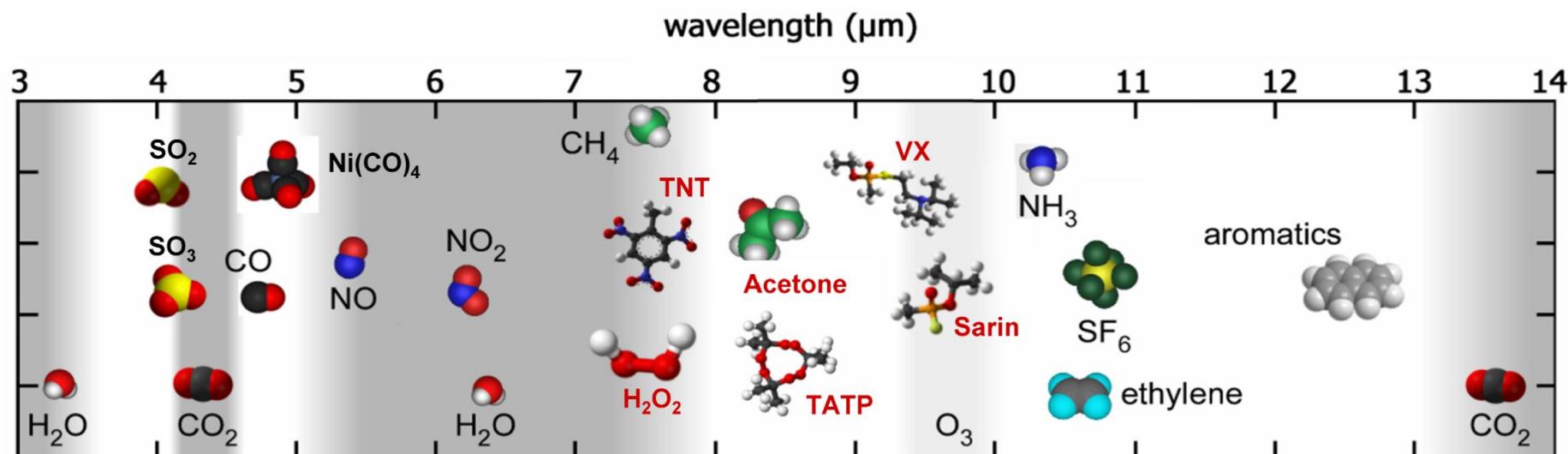
Ponderomotive force

$$F_P \propto I_{laser} \lambda^2$$

Pump-probe
experiments

Mode-selective
chemistry

Attosecond
science



Current ultrashort IR sources

MIR sources	Energy	Pulse duration	Peak power	Wavelength range
CO ₂ laser ¹	45 J	3 ns	15 TW	~10 μm
Mid-infrared fiber laser ⁵	150 nJ	~100 fs	~1.5 MW	1.4~13.3 μm
MIR-FEL ⁶	Macro: 6-8 mJ Micro: 2-2.7 μJ	Macro: 2 μs Micro: 2 ps	~1 MW	5~16 μm

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

[2] Yuxi Fu, et al. Appl. Phys. Lett. 112, 241105(2018)

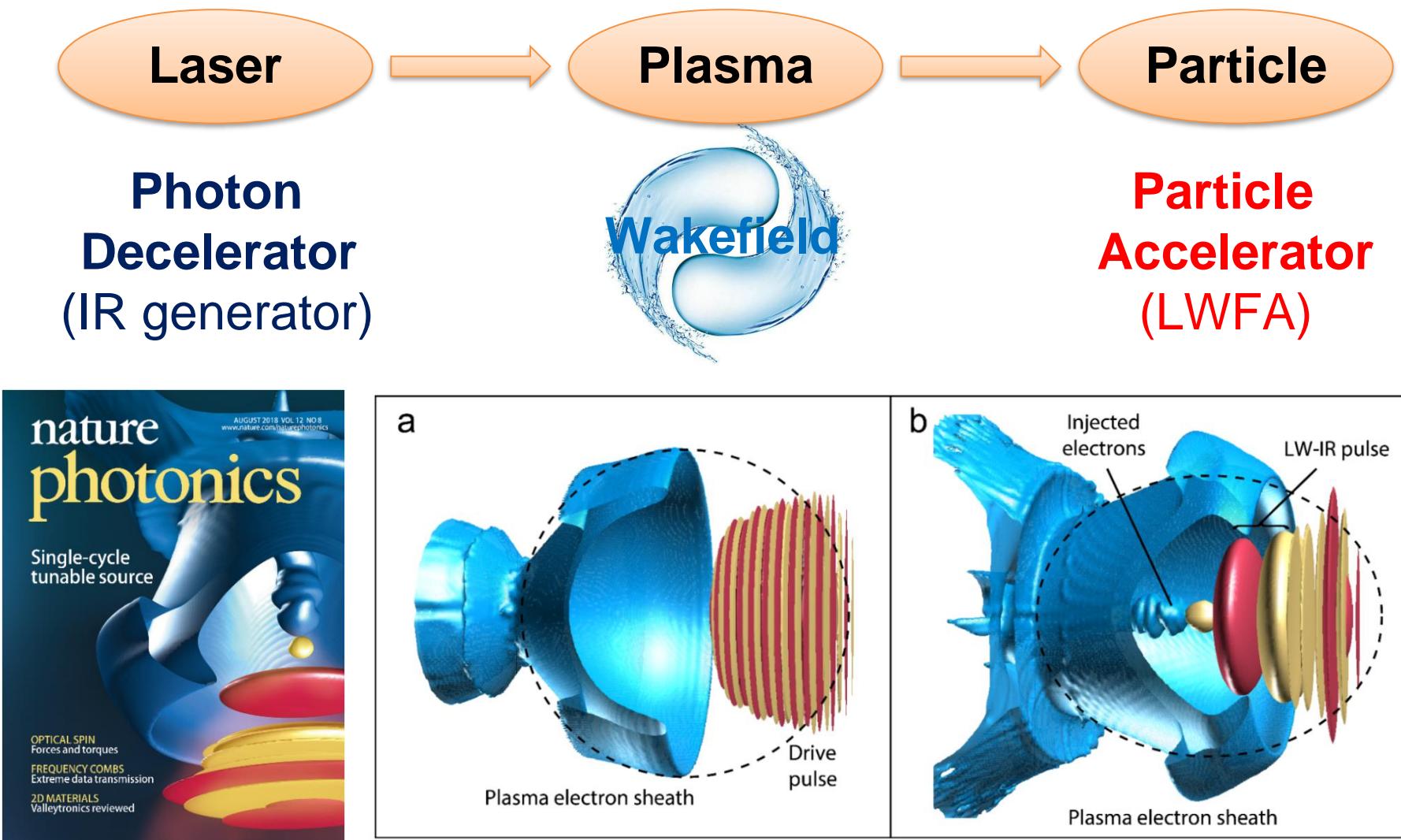
[3] Peter Krogen, et al. Nat. Photonics 11, 222(2017)

[4] Takao Fuji, et al. Opt. Lett. 32, 3330(2007)

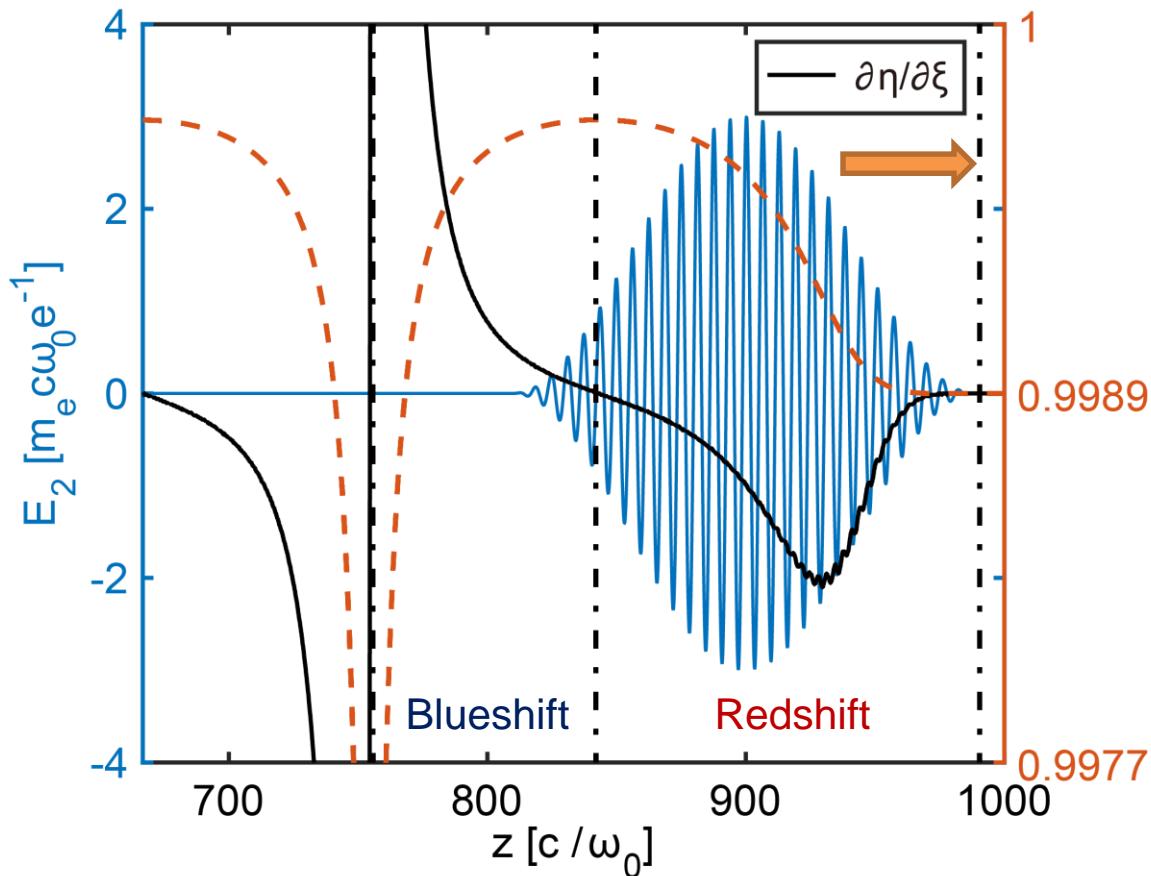
[5] I. Pupeza, et al. Nat. Photonics 9, 721(2015)

[6] Kyohei Yoshida, et al. Energy Procedia 9, 483(2011)

Laser-plasma interaction



Photon deceleration



Self-phase modulation: $\frac{1}{k} \frac{\partial k}{\partial(c\tau)} = \frac{1}{\eta^2} \frac{\partial\eta}{\partial\xi}$

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

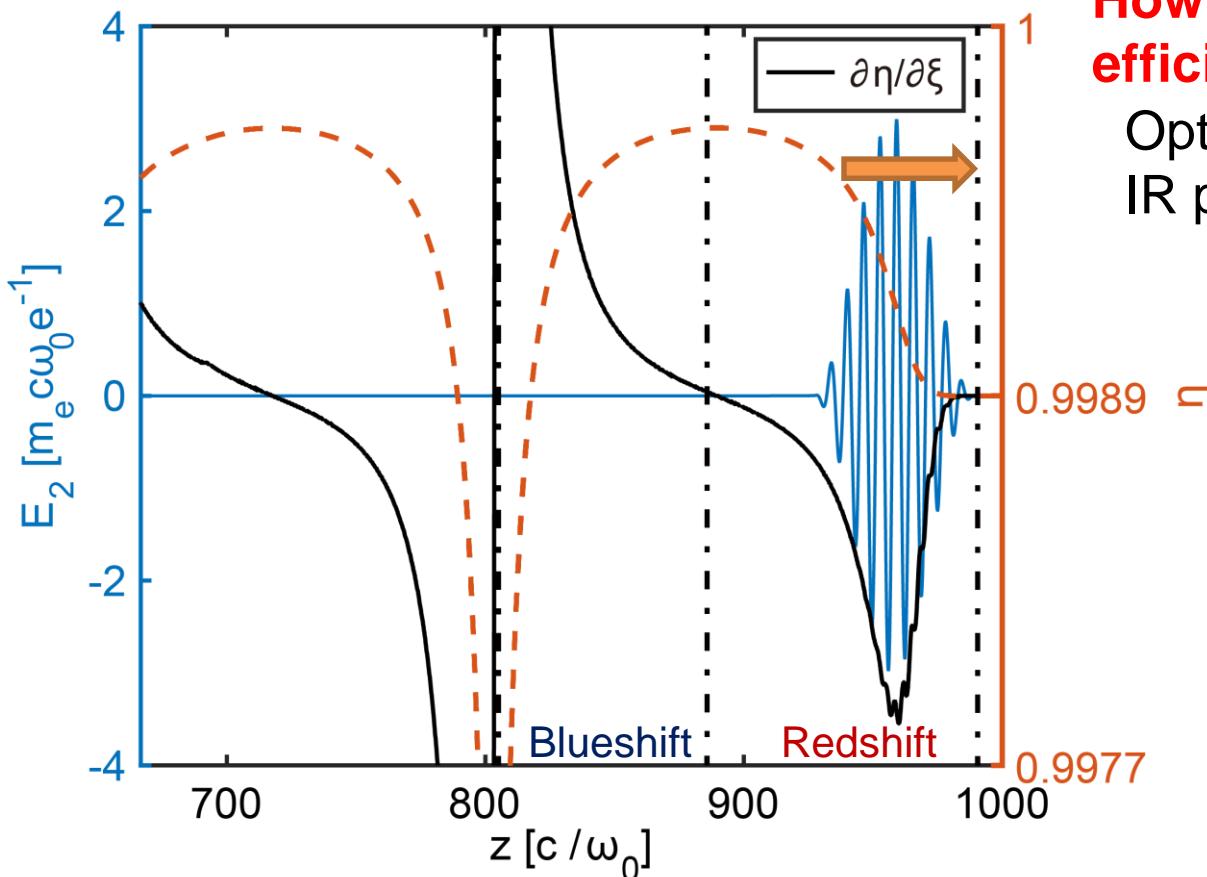
Theory and simulations:

- 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)

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



Self-phase modulation: $\frac{1}{k} \frac{\partial k}{\partial (c\tau)} = \frac{1}{\eta^2} \frac{\partial \eta}{\partial \xi}$

$$\frac{1}{k} \frac{\partial k}{\partial (c\tau)} = \frac{1}{\eta^2} \frac{\partial \eta}{\partial \xi}$$

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

How to increase conversion efficiency?

Optimal pulse duration for IR pulse generation

$$(a_0 \gg 1)$$

$$c\tau \approx \frac{0.52\lambda_p}{a_0}$$

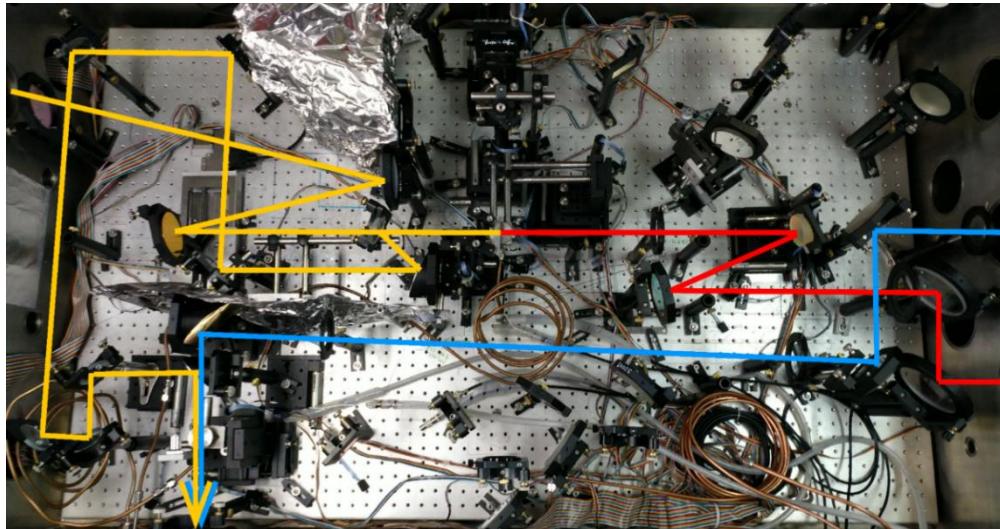
$$\begin{cases} n_p = 4 \times 10^{18} \text{ cm}^{-3} \\ a_0 = 3 \end{cases} \Rightarrow \tau = 9.6 \text{ fs}$$

Demonstration of ultra-intense single-cycle IR generation

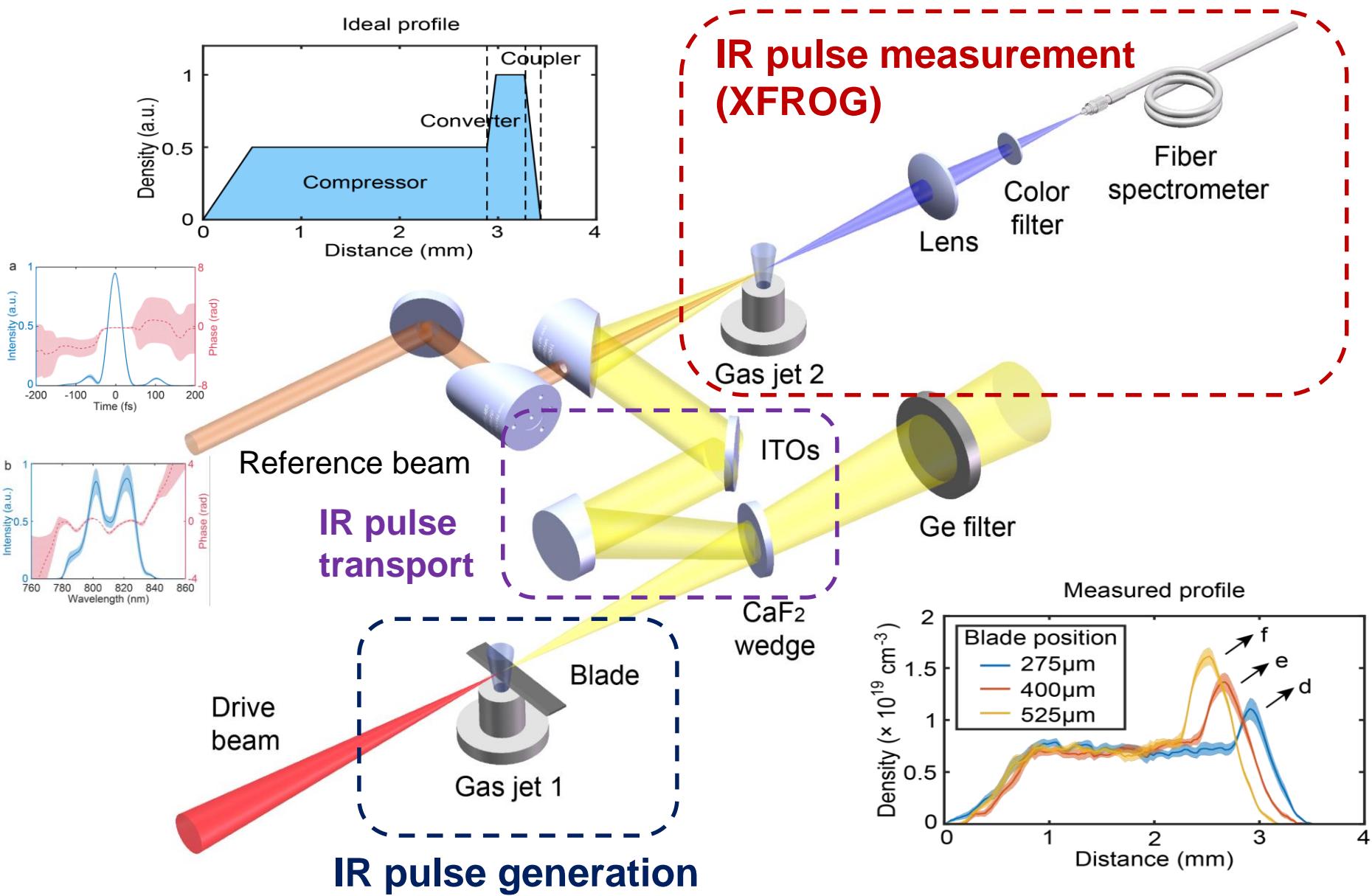
T.-S. Hung et al., *Appl Phys B*,
117, 1189 (2014)



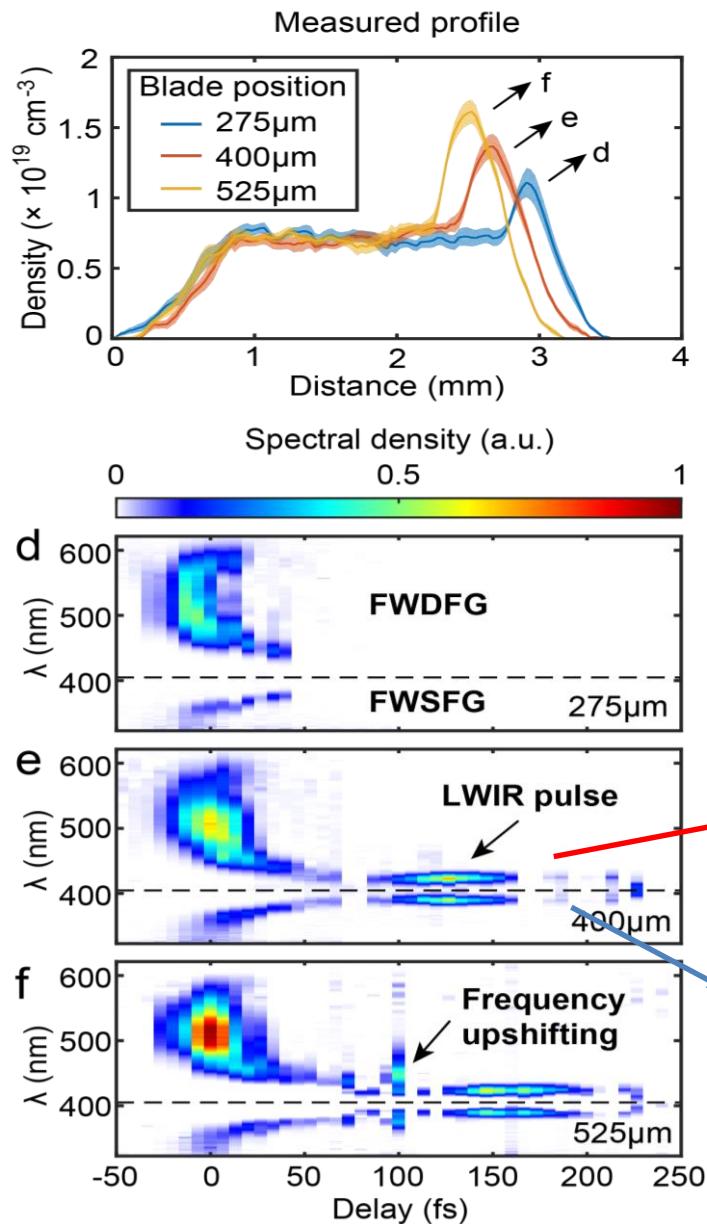
100 TW laser platform at National Central University



Schematic of experimental setup



Optimization of plasma structures— blade scanning



FWDFG

$$\omega_0 + \omega_0 - \omega_{IR} \rightarrow \omega_{FWDFG}$$

FWSFG

$$\omega_0 + \omega_0 + \omega_{IR} \rightarrow \omega_{FWSFG}$$

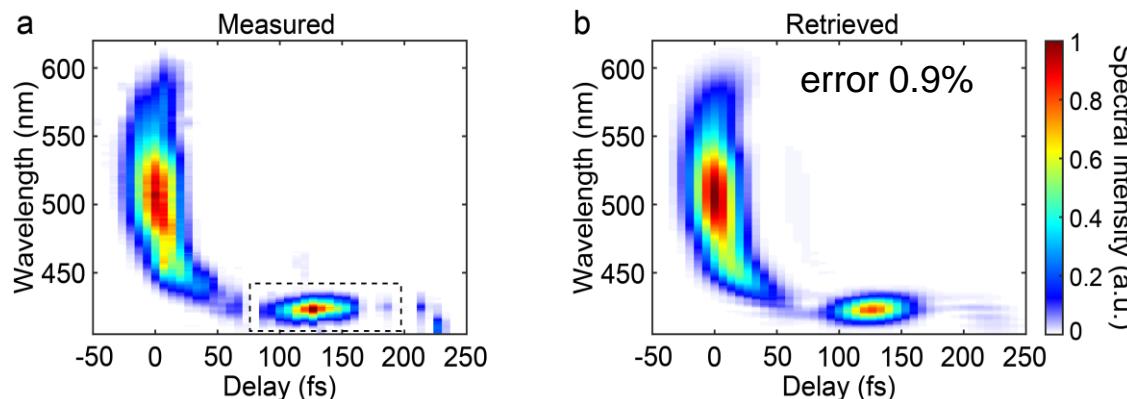
423.0 nm

405.0 nm

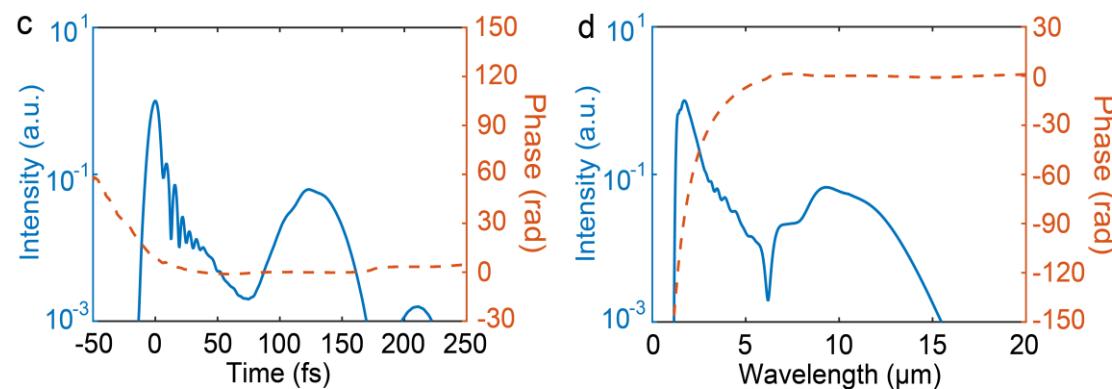
389.5 nm

Retrieved IR pulse

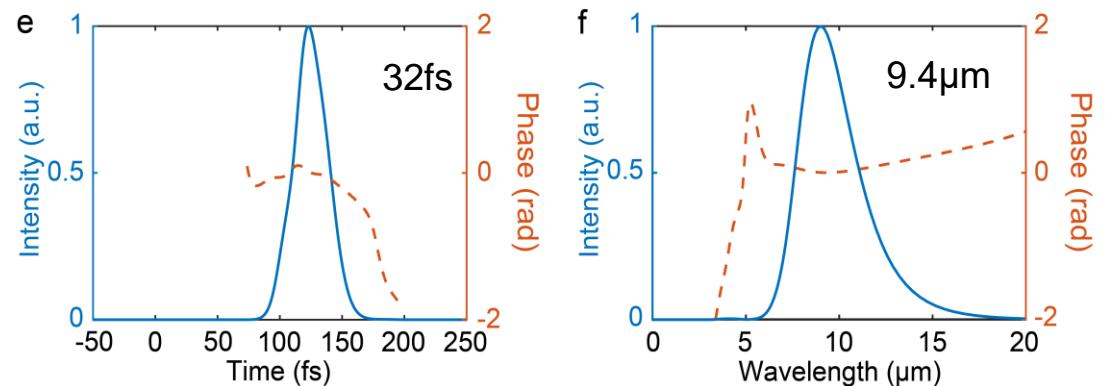
XFROG trace:



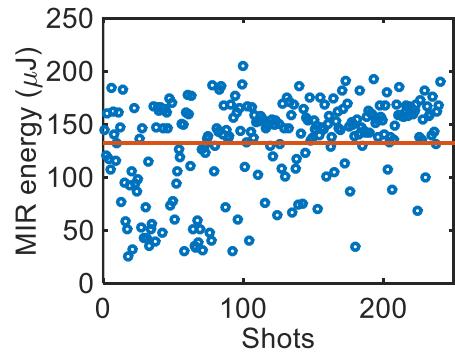
IR pulse:



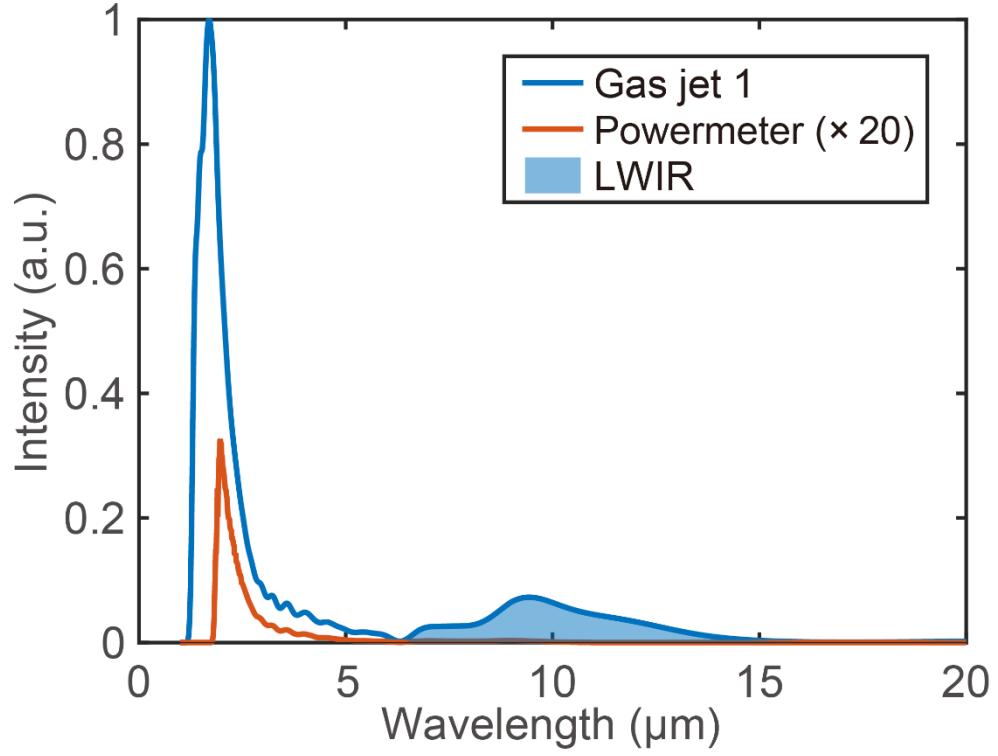
LWIR pulse:



IR spectrum and energy

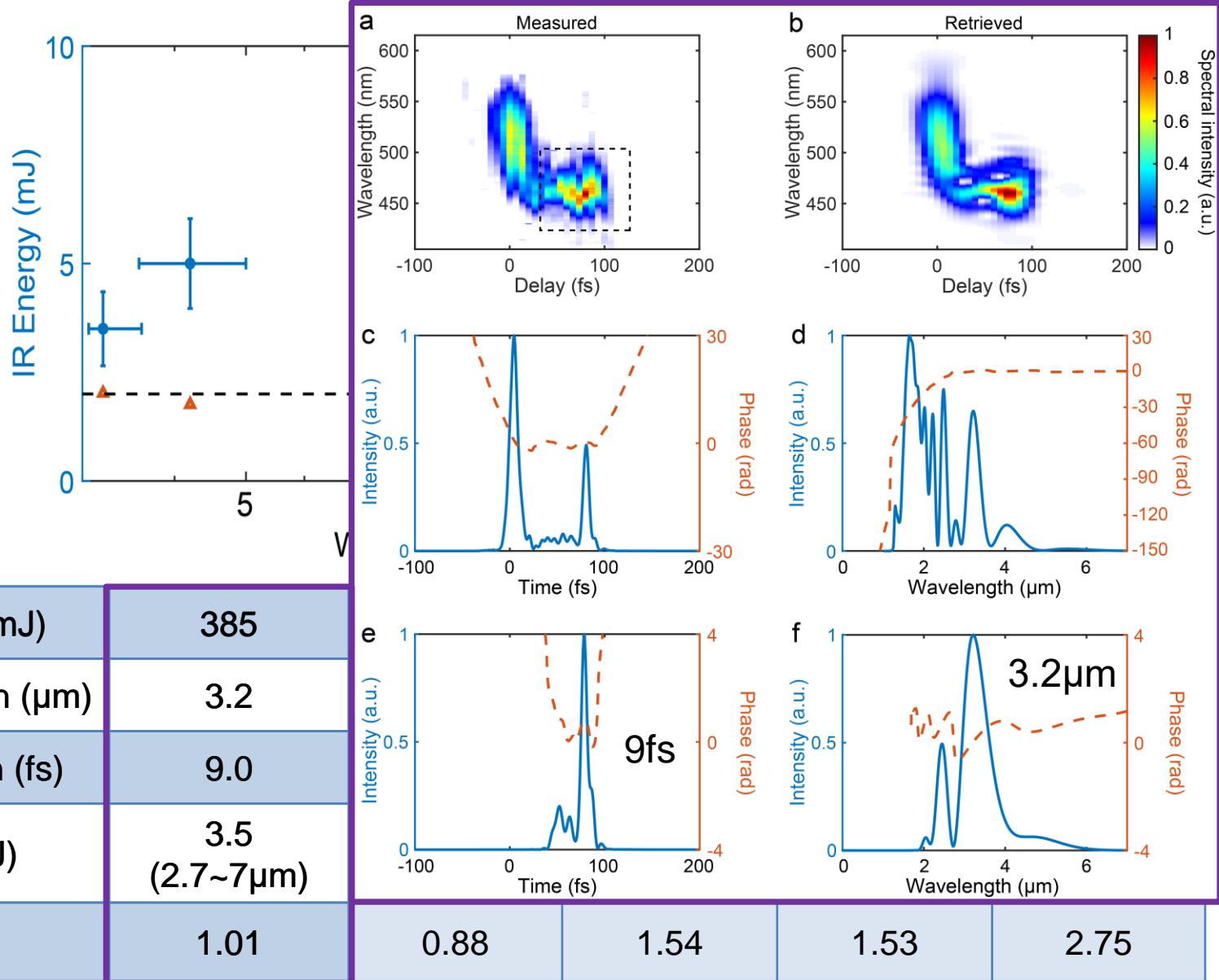


Measured IR energy:
 $132.5 \pm 42.0 \mu\text{J}$

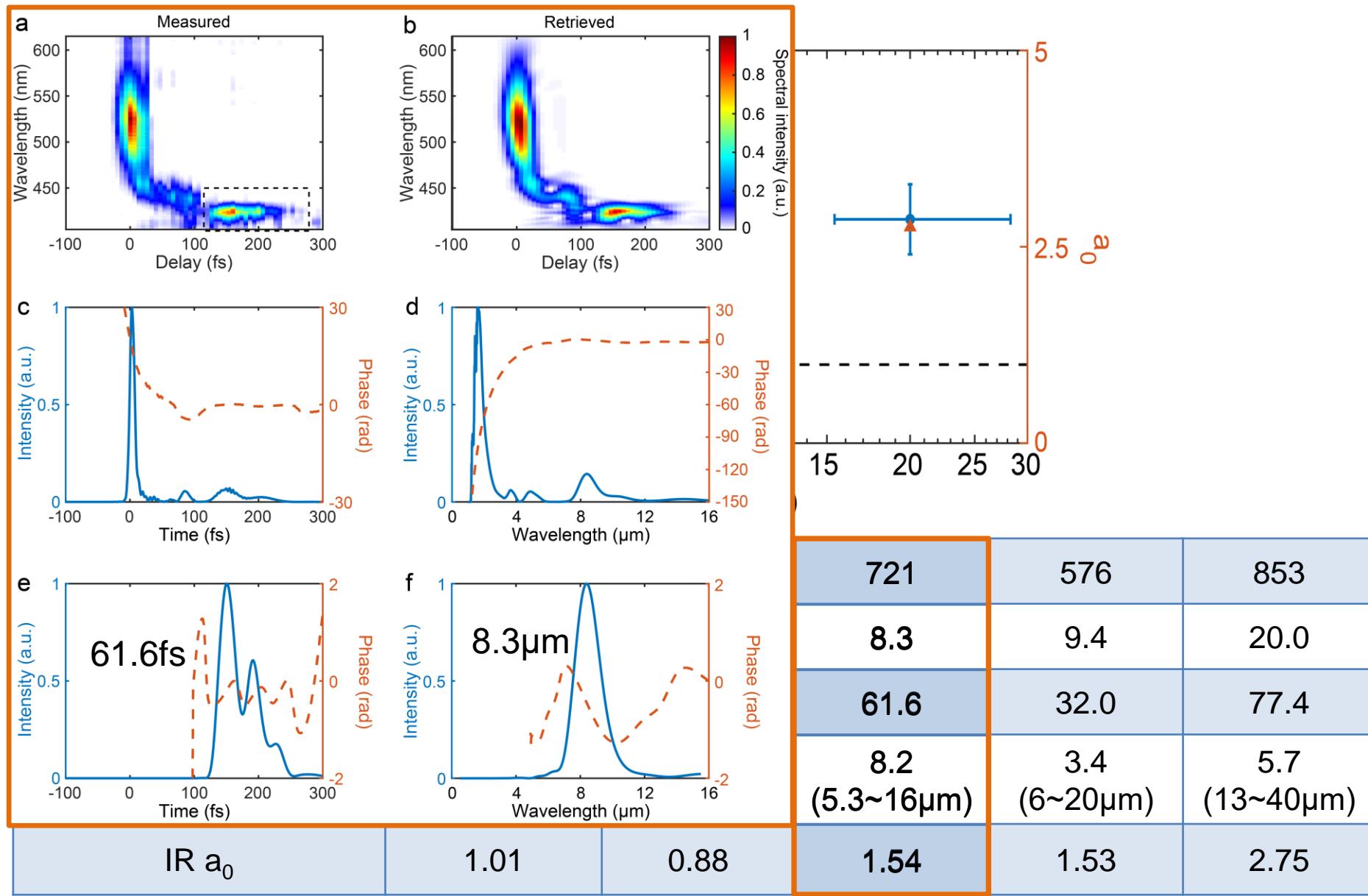


Central wavelength	9.4 μm
Pulse duration (FWHM)	33 fs
LWIR energy (6-20 μm)	(3.41 ± 1.08) mJ
LWIR efficiency (6-20 μm)	(0.84 ± 0.27)%
Peak power	(103 ± 33) GW
Peak a_0	1.53 ± 0.25
Electric field	(0.52 ± 0.08) TV/m
Overall energy (1.2-20 μm)	> (15.0 ± 4.8) mJ
Overall efficiency (1.2-20 μm)	> (3.7 ± 1.2)%

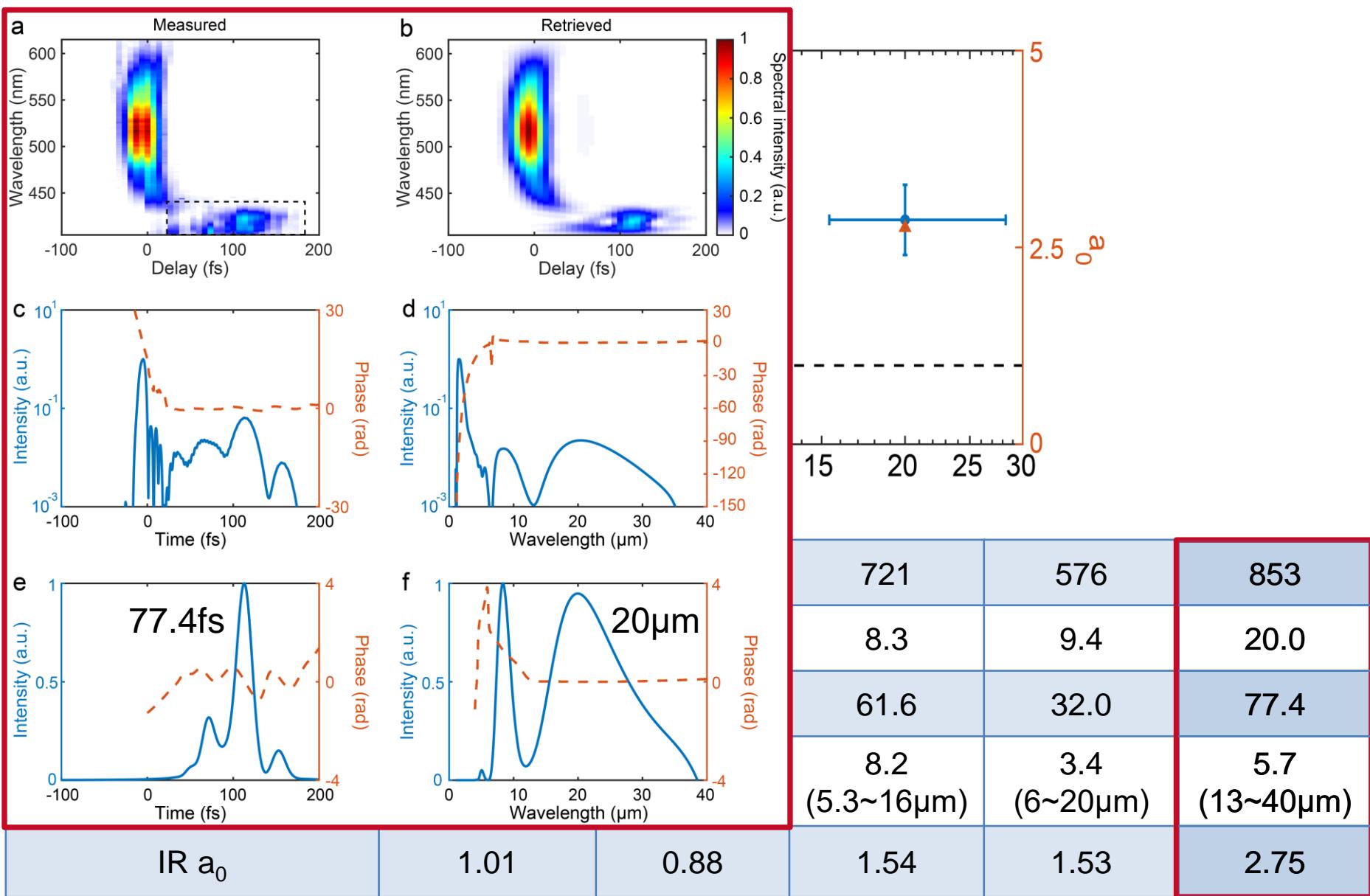
Wavelength tunability



Wavelength tunability



Wavelength tunability



Summary

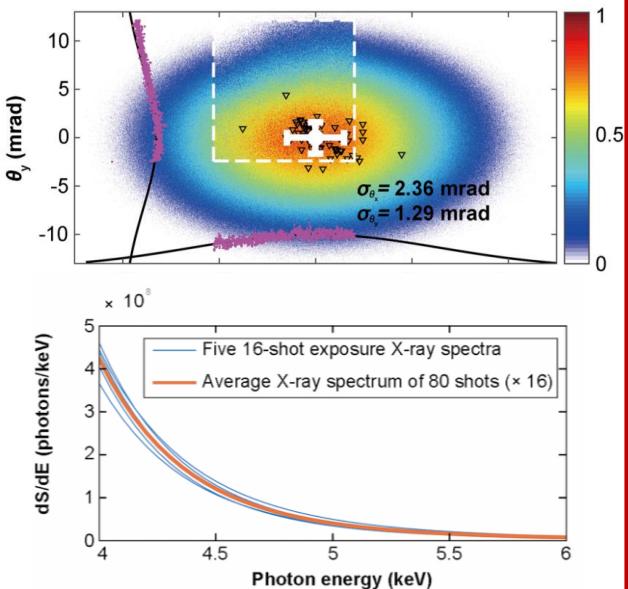
- High-quality electron beams with very low absolute energy spread using a 30-fs 50-TW laser was achieved.
- Direct visualization of wakefield structure in a laser plasma accelerator using a fs relativistic electron probe was achieved.
- High quality PCIs were obtained by multiple shots accumulation, with a resolution of $5.5 \mu\text{m}$. For the first time, we took PCIs of a fish using betatron source.
- A new scheme of generating relativistic single-cycle long-wavelength infrared pulses by a density-tailored plasma structure, which will be very useful for strong field applications.

Thank you for your attention.

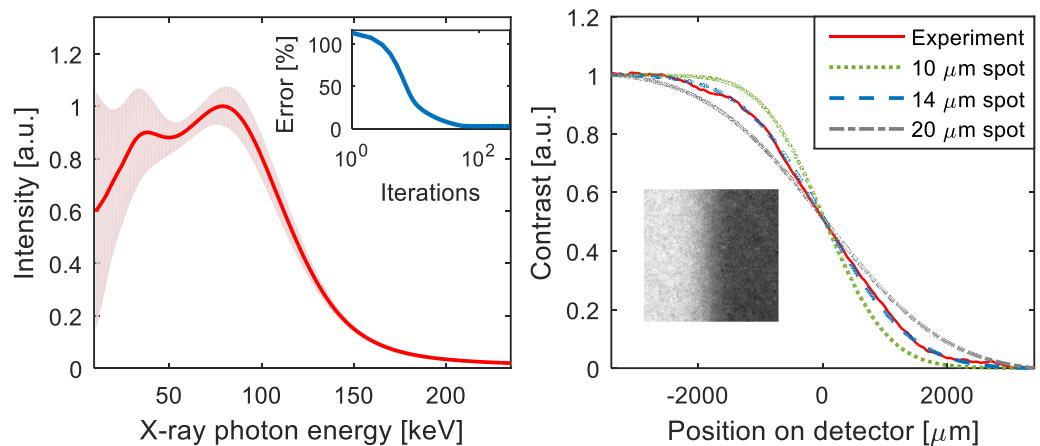
Tabletop laser-driven light sources

➤ We have demonstrated the most stable tabletop light sources

- Betatron radiation



- All-optical Thomson scattering



➤ photon flux: 8×10^9 photons/shot