

IPAC
2026

17th International
Particle Accelerator Conference

May 17 - 22
Deauville | Normandy | France

Compact Laser wakefield accelerator and Free-electron lasing

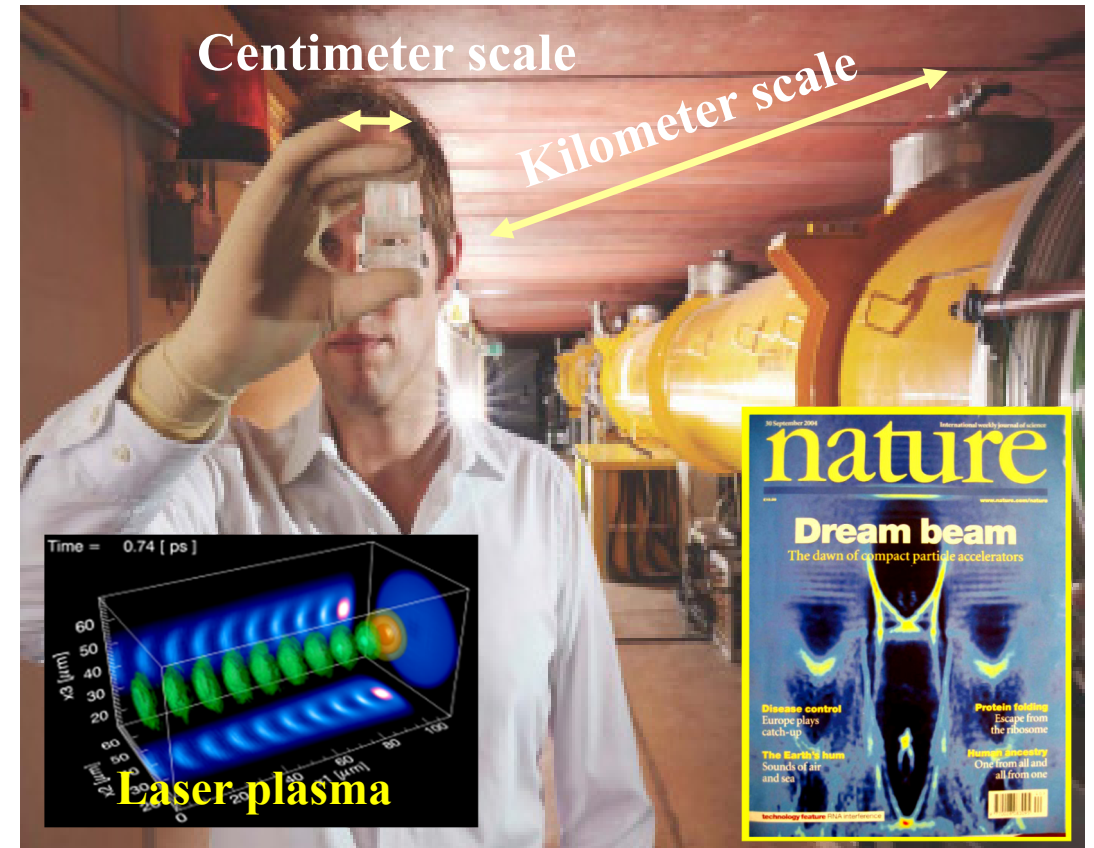
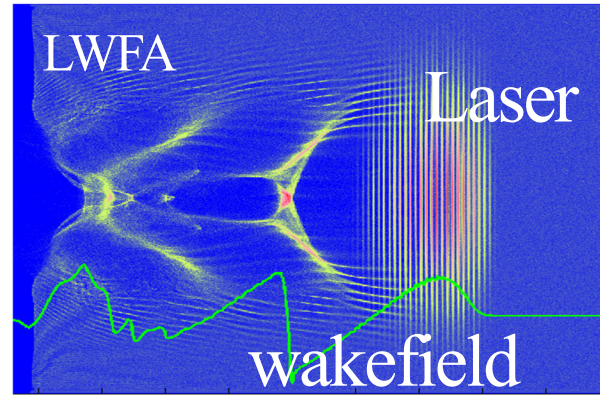
Wentao Wang

Shanghai Institute of Optics and Fine Mechanics (SIOM)
Chinese Academy of Sciences (CAS)

Laser wakefield acceleration and “Dream Beams”

Laser wakefield acceleration was proposed in 1979

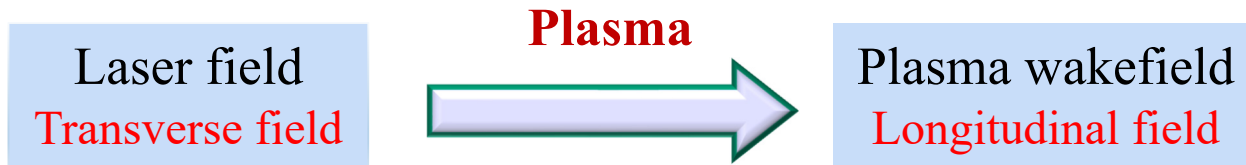
From kilometer scale to centimeter scale



T. Tajima

J.M. Dawson

Phys. Rev. Lett. 43, 267(1979)



Without breakdown voltage $\sim 100\text{GV/m}$

So, LWFA's hold great possibility to develop small-size accelerators and driving compact radiation sources.

Rapid Developments of Laser wakefield accelerators

Low energy spread and high quality

Nature ×3 (2004) “Dream beam”	~10%
Phys. Rev. Lett. 117 124801 (2016)	0.4-1.2%
Phys. Rev. Lett. 126 104801 (2021)	0.7%
Phys. Rev. Lett. 126 214801 (2021)	0.24-0.41%
Nature 640 , 907–910 (2025)	<permille level

.....

Cascaded and high energy acceleration

Nat. Comm. 4 , 1988 (2013)	Accel. With PW laser
Phys. Rev. Lett. 113 , 245002 (2014)	4.3GeV
Nature 530 , 190–193(2016)	Cascaded
Phys. Rev. Lett. 122 , 084801 (2019)	7.8 GeV
Phys. Rev. Lett. 133 , 255001 (2024)	9.2 GeV

.....

LWFA

High charge / high efficiency

Phys. Rev. X 10 041015 (2020)	~2 nC
High Energy Density Phys. 37 100859 (2020)	~50 nC
Sci. Rep. 11 7498 (2021)	~700 nC
Laser Photon. Rev. 17 2300514 (2023)	~20 nC
Phys. Rev. Lett. 133 , 045002 (2024)	~nC/GeV

.....

High stability and high repetition

Nat. Photon. 2 , 571–577 (2008)	Stable generation
Phys. Rev. Lett. 110 .185006 (2013)	Shock injection
Phys. Rev. X 10 031039 (2020)	100000 shots@1 Hz
Phys. Rev. Lett. 126 174801 (2021)	Bayesian opt.
PRAB 25 031301 (2022)	75000 shots@2.5 Hz

.....

There are still many important advances in LWFA that cannot be listed one by one. 3

Free-electron laser is an important sign that shows the application of LWFA

- **Table-top FEL** is very important, not only for scientific progress, but also for the future of LWFA.
- Photon yield is the foundation of applications. **Low-charge LWFA can generate high-brightness FEL!**

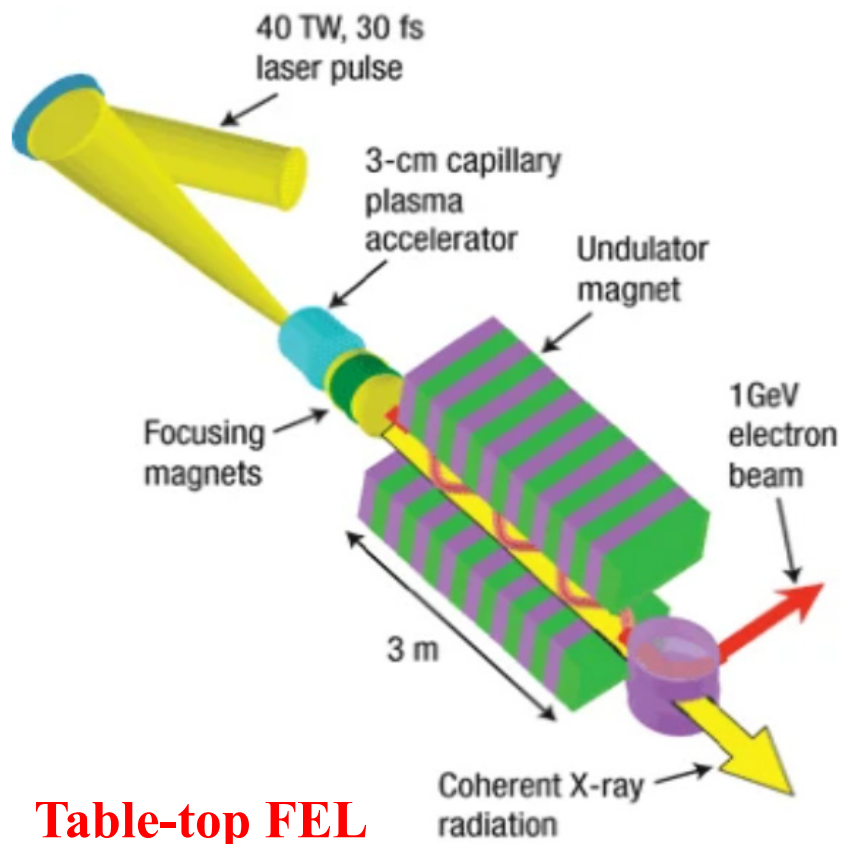
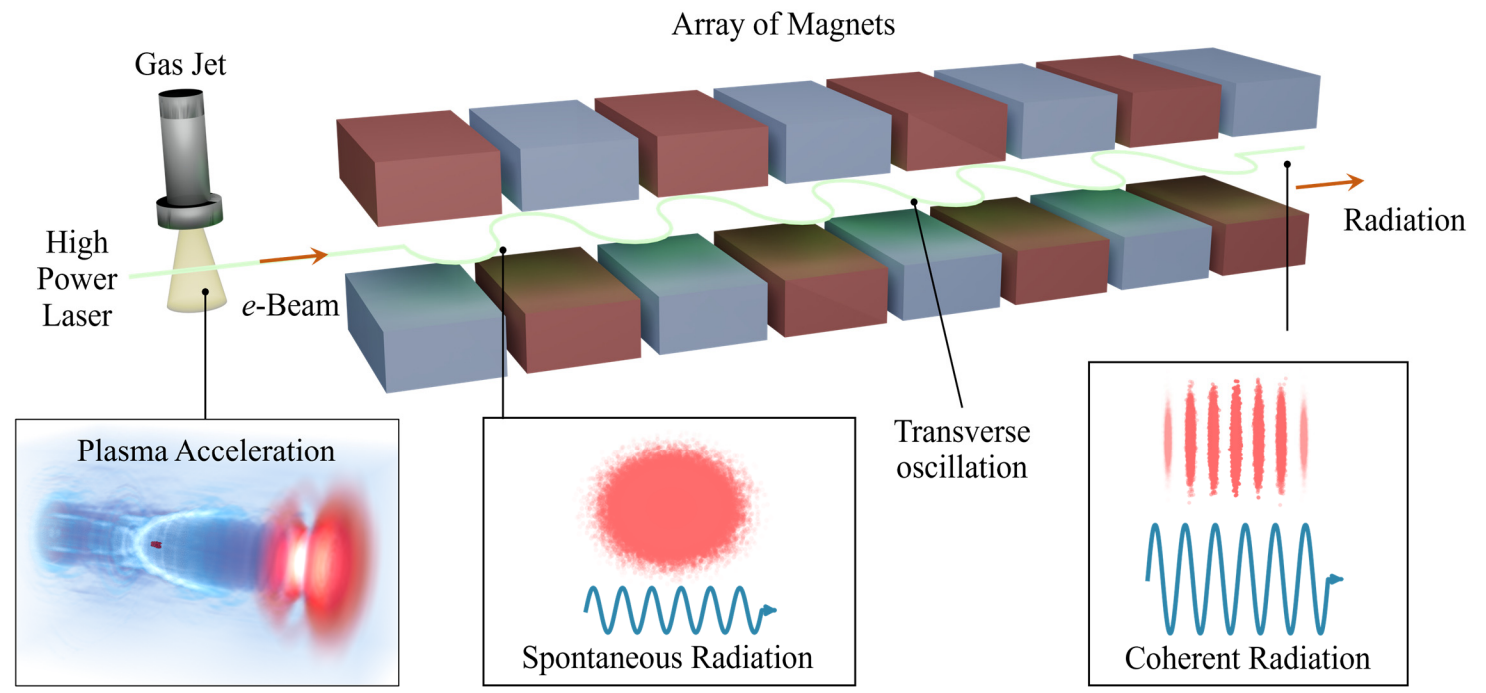


Table-top FEL

K. Nakajima, *Nat. Phys.* **4** (2008).

From ~30pC to ~10μJ

Incoherent radiation $P \sim N \quad 10^{6-9}$
 Coherent radiation $P \sim N^2 \quad 10^{10-12}$



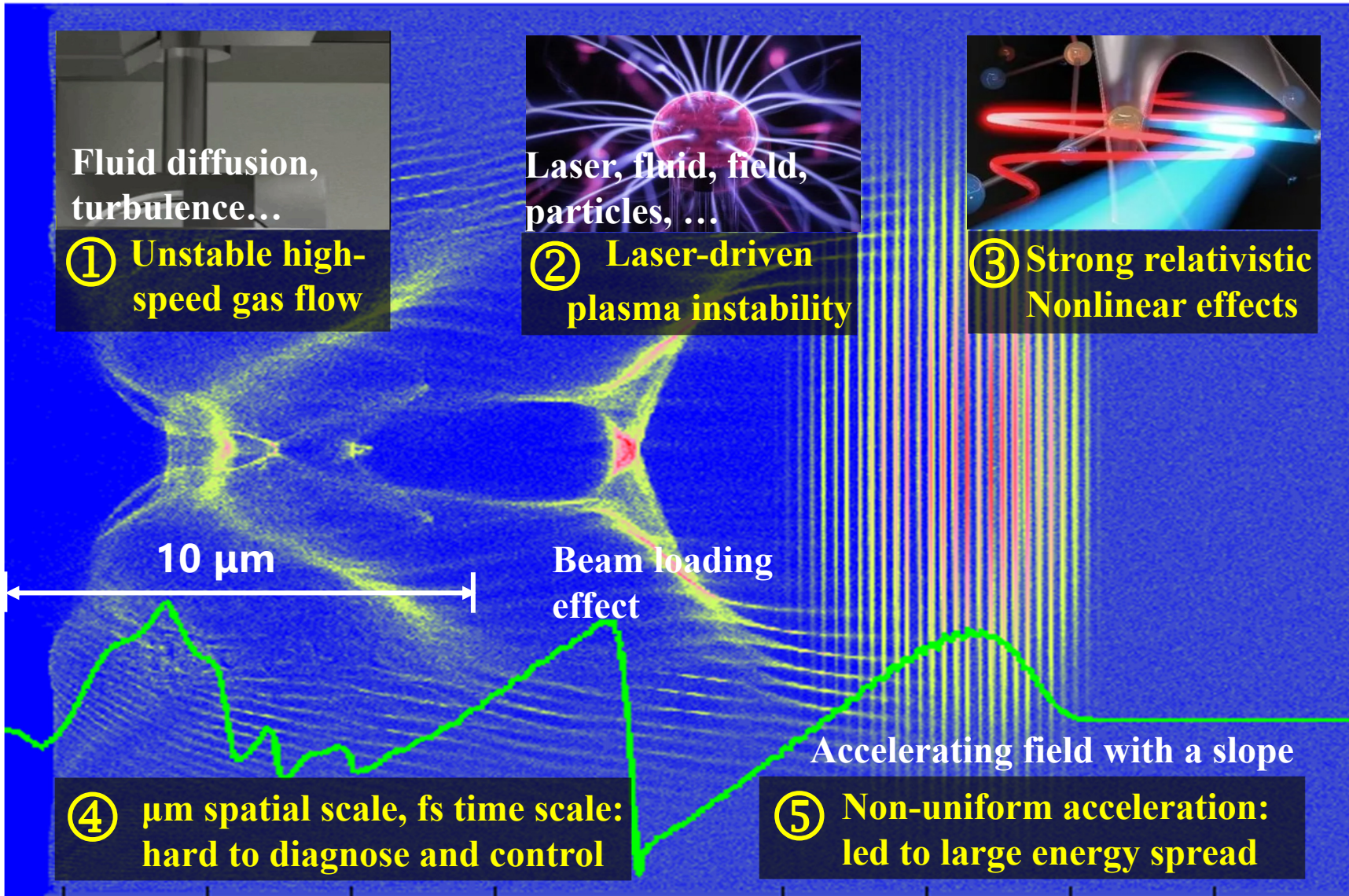
Projects about table-top FELs based on LWFAs



C. Emma, et. al, High Power Laser Science and Engineering 9, e57 (2021)

Our team has been focusing on this since 2011 — A decade-long experiment. (NSFC 11127901) 5

LWFA faces many challenges and a huge gap to compact FELs



In 2011, when we started:

Electron Beam from LWFA

- ❑ 5% energy spread ❌
- ❑ mm emittance ❌
- ❑ 100 A- 1kA current intensity ✅
- ❑ Unstable, no repetition ❌

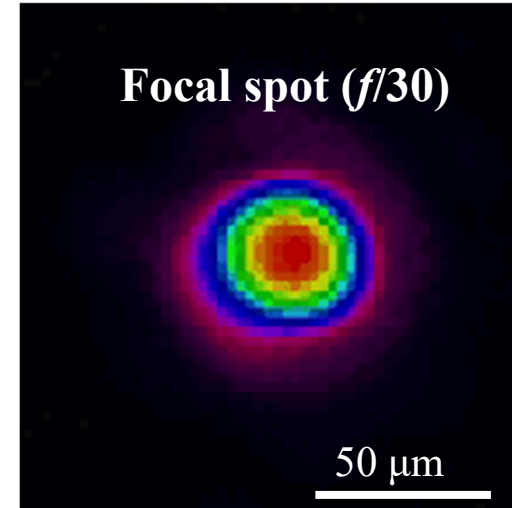
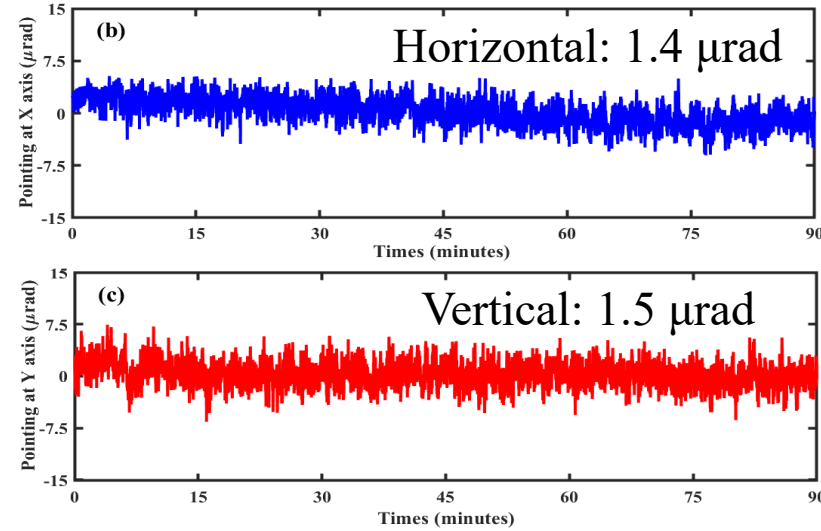
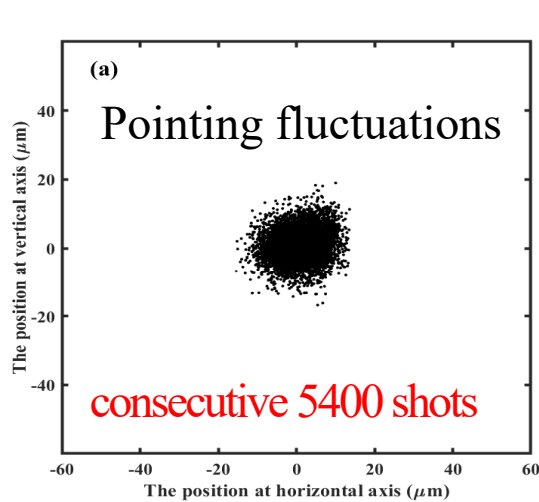
“Huge Gap”

Compact FELs need:

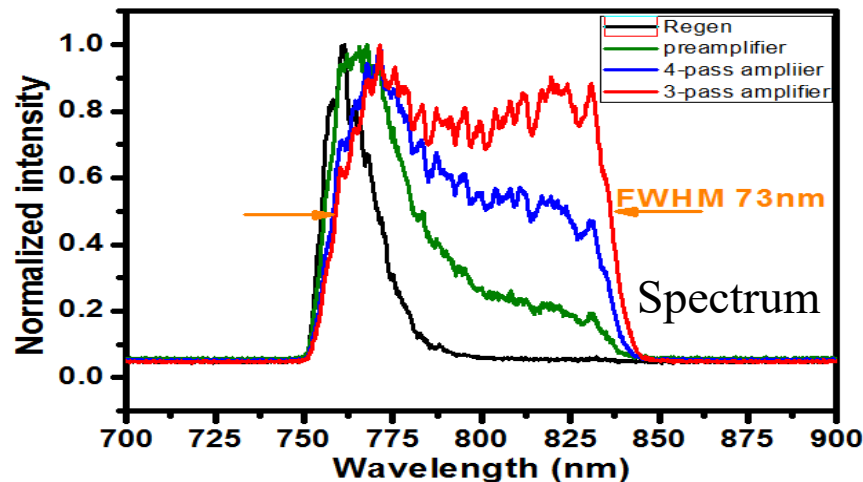
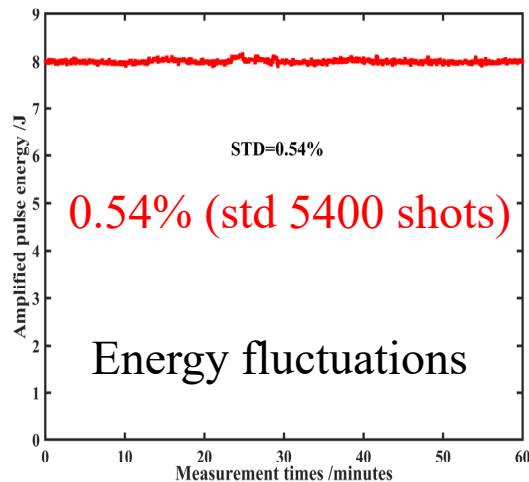
High-quality electron Beam

- ❑ 0.2% energy spread
- ❑ 2 μm emittance
- ❑ 1kA current intensity
- ❑ 1 Hz repetition frequency

Self-made 200TW laser system and its performance improvement (2013-2023)



Prof. Yi Xu
@SIOM



Performance of 200 TW/1Hz laser system:

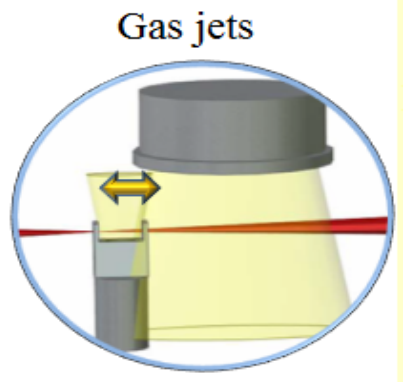
- Laser energy: 8J / 0.54% (std);
- Focal spot($f/30$): 52 μm ($1/e^2$) / 58.4%;
- Pointing stabilities: 1.4 μrad /1.5 μrad ;
- Pulse duration: 24 fs.

Opt. laser Technol. 131, 106453(2020)

This laser has supported our experiments for 10 years, over 300 days per year, 8 hours per day! 7

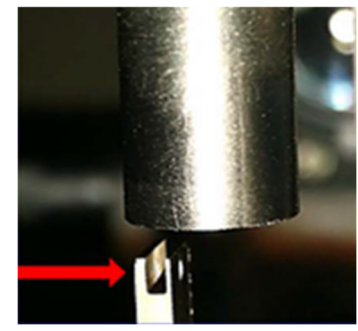
High quality electron beam generation: A 10-year-long, ongoing experiment

Version 1.0



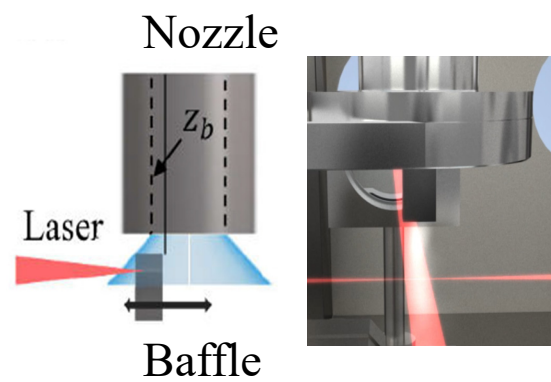
Energy spread <math><1\%</math>

Version 1.0 +



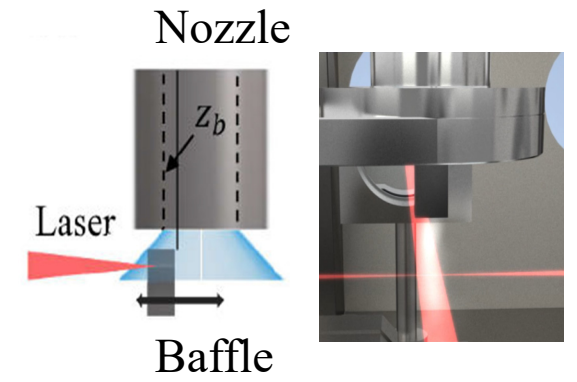
Energy spread <math><0.5\%</math>

Version 2.0

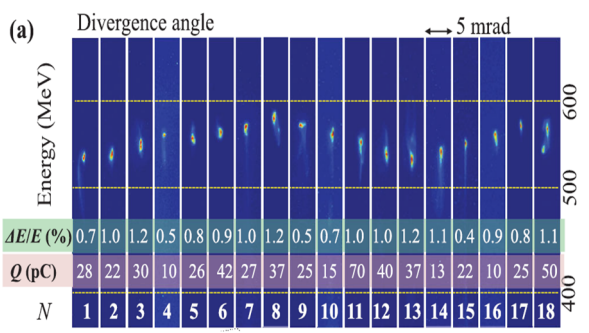


Energy spread <math><0.2\%</math>

Version 2.0 + (recently)

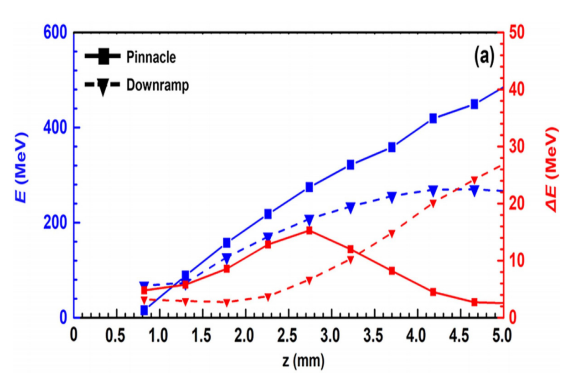


Energy spread of $\sim 0.1\%$



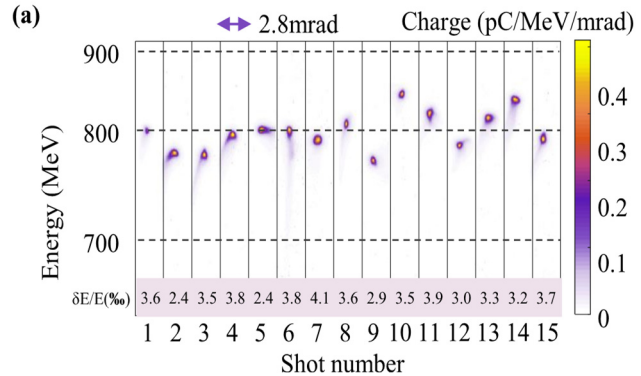
e beam phase modulation to compress the energy chirp

Phys. Rev. Lett. **117** 124801 (2016).



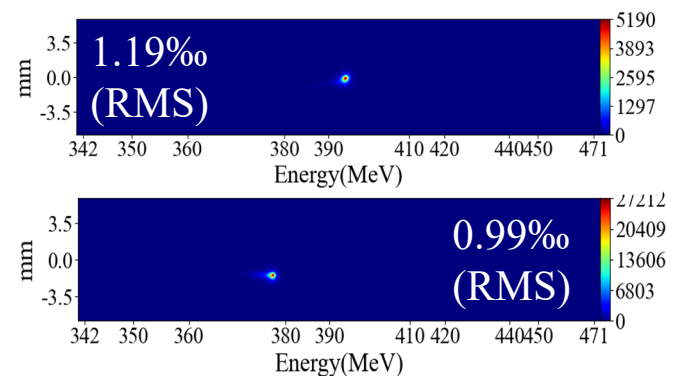
Single stage: large initial chirp and compensation

PPCF **60**, 075008 (2018)



Energy spread optimization by laser defocusing and beam-loading

Phys. Rev. Lett. **126** 214801 (2021)

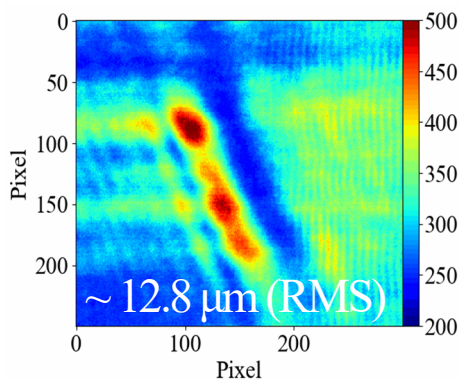


Energy chirp control and slice energy spread optimization

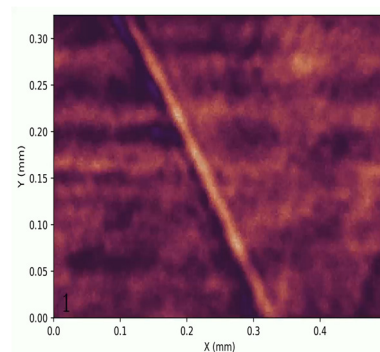
Ke Feng *et al.* in preparation.

Stabilities improvement of LWFA (2013-Now)

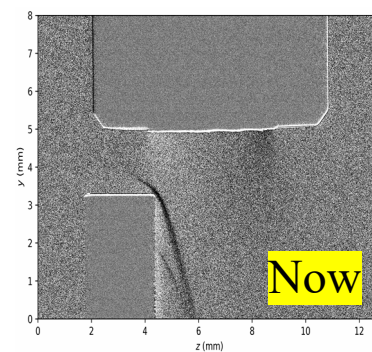
Upgradation of the gas target
to reduce density shock jitter



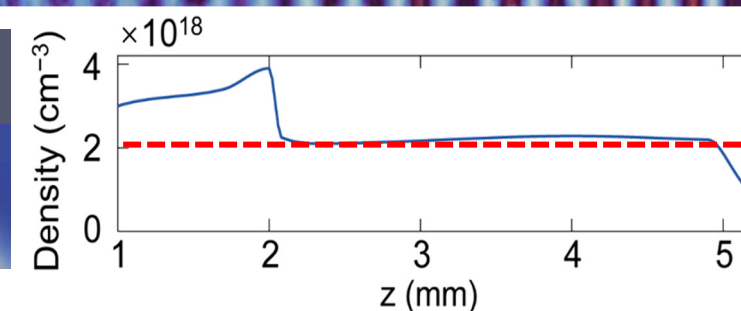
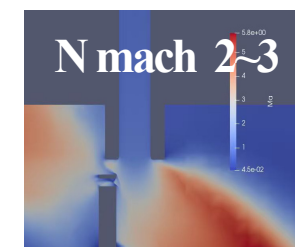
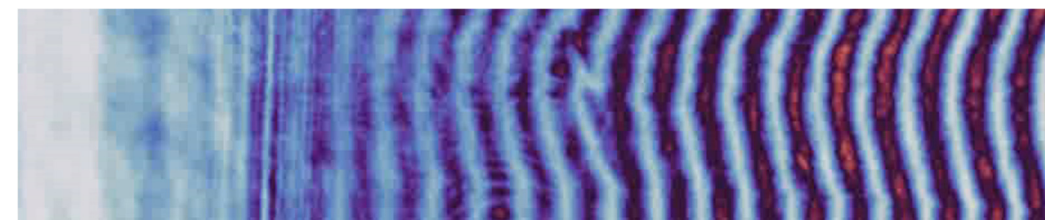
Before Upgradation
 $\sim 12.8 \mu\text{m}$ (RMS)



Change gas nozzle
 $< 4.9 \mu\text{m}$ (RMS)



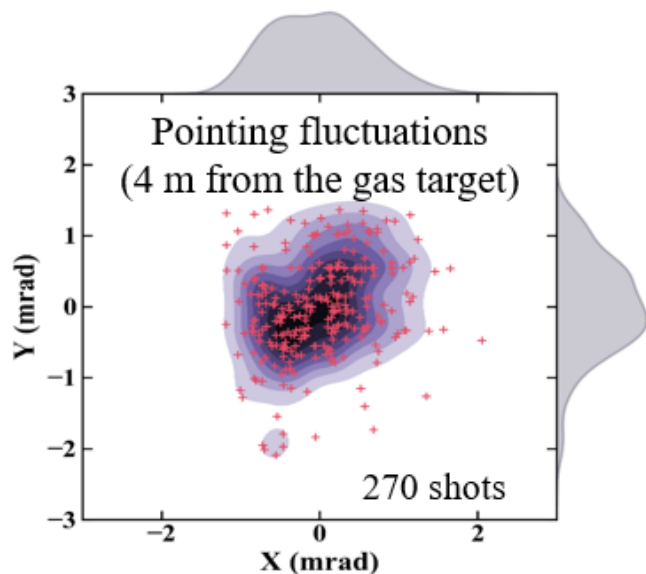
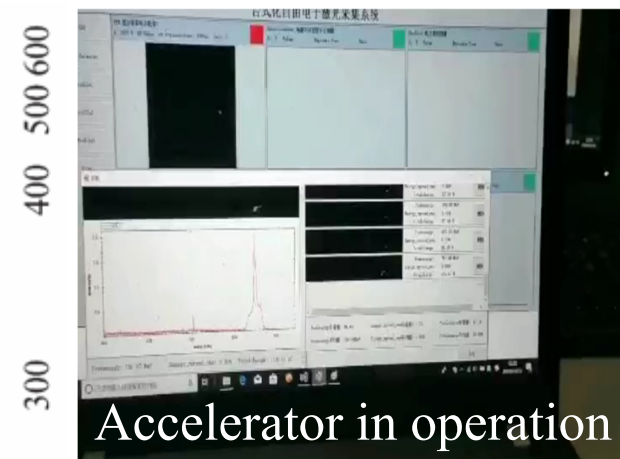
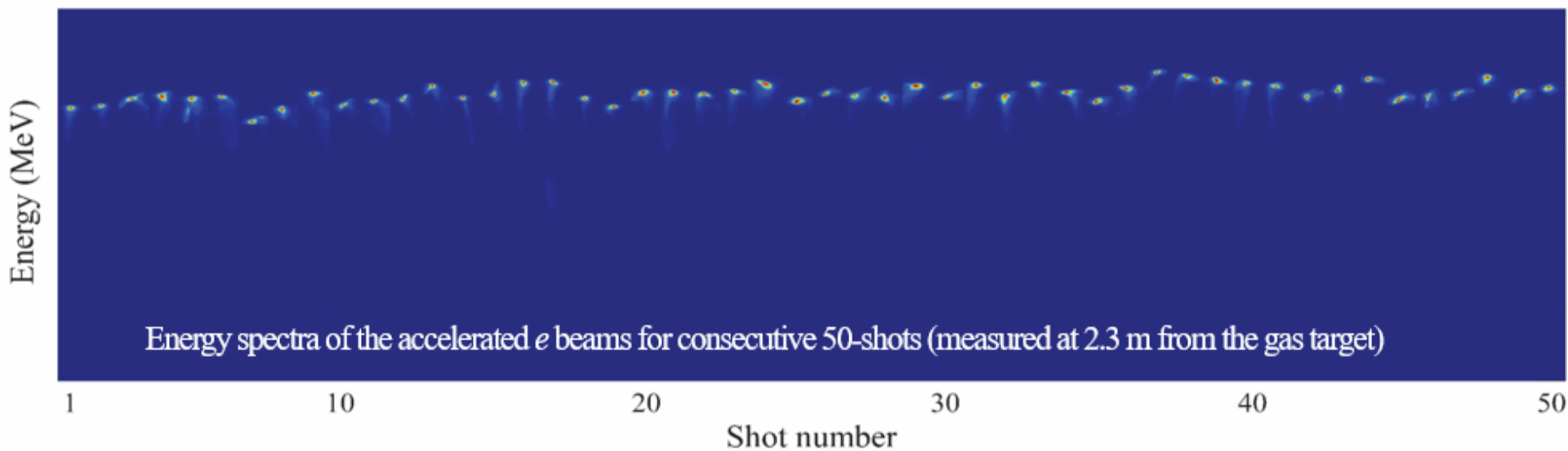
Change support frame
 $\sim 1 \mu\text{m}$ (RMS)



Minimize plasma density $\sim 5 \times 10^{18} \text{cm}^{-3} \rightarrow \sim 2 \times 10^{18} \text{cm}^{-3}$

- The supersonic gas flow can be adjusted by changing the structure of the Laval nozzle, and the Mach number is 2~3.
- Minimize the plasma density can reduce the influence of nonlinear effects.

Stable and high-quality electron beams generation from LWFAs



Beam properties

- Peak energy stabilities (std) < 3%
- Energy spread ~ 0.2-1.2%
- Charge ~ 10-50 pC
- Divergence ~ 0.1-0.4 mrad
- Pointing stability (std) = 0.6~1 mrad

Acceleration
Reproducibility ~ 30%



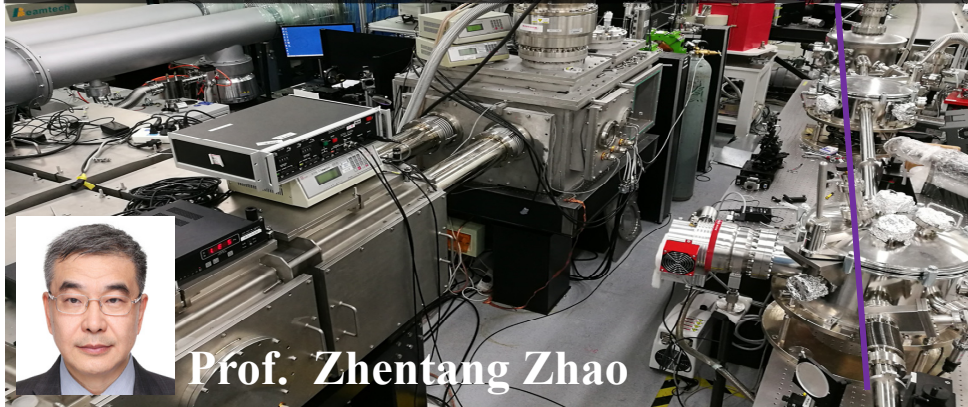
Accelerator
Reproducibility 100%



Compact FEL!

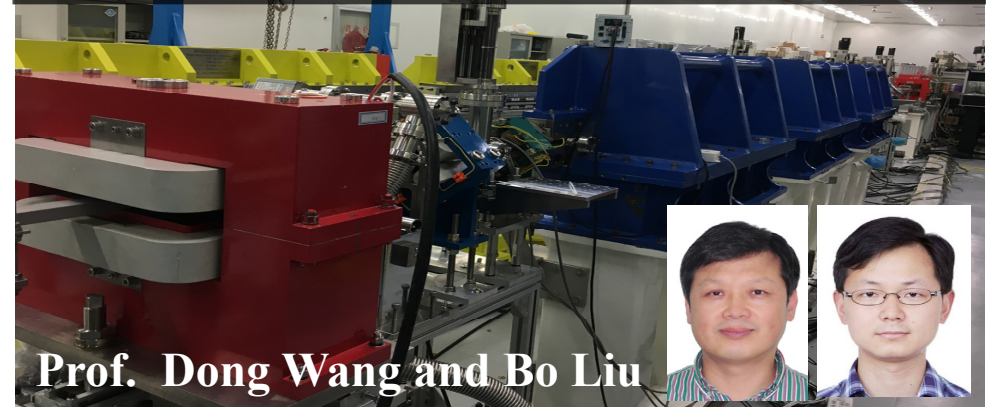
We tried different implementation paths for the FEL (2014-2018)

2014-2015: Initial scheme of the project
High-order harmonic seeding scheme



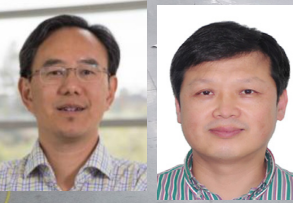
Prof. Zhentang Zhao

2015-2016: Second scheme with SINAP
Long-distance planar undulator scheme (20m)



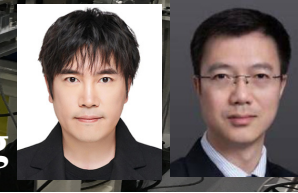
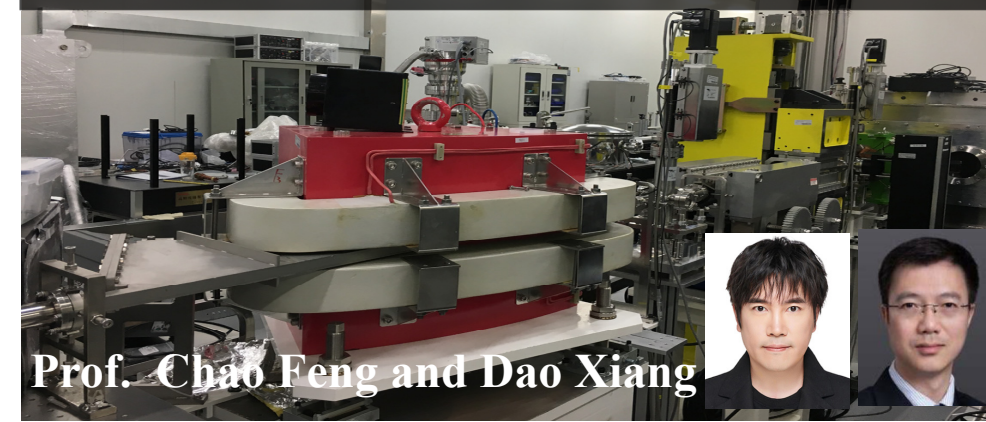
Prof. Dong Wang and Bo Liu

2016: Third scheme with SINAP and ZR. Huang
TGU undulator scheme



Prof. Zhirong Huang
and Dong Wang

2018-2023: Forth scheme with SARI
Pre-bunched scheme

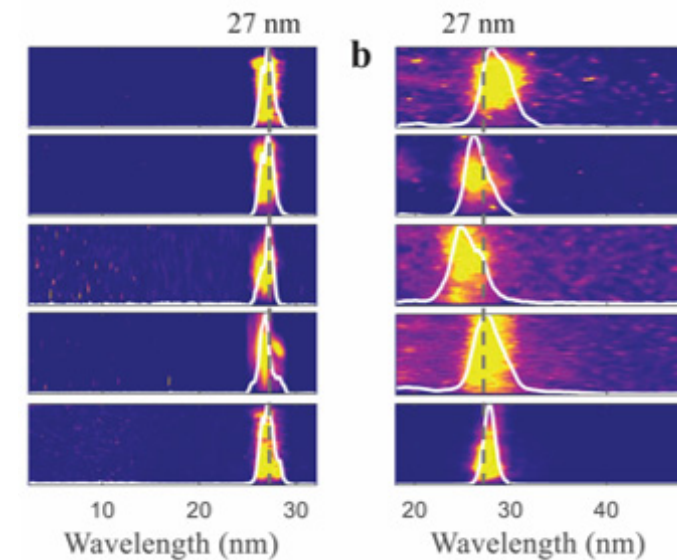
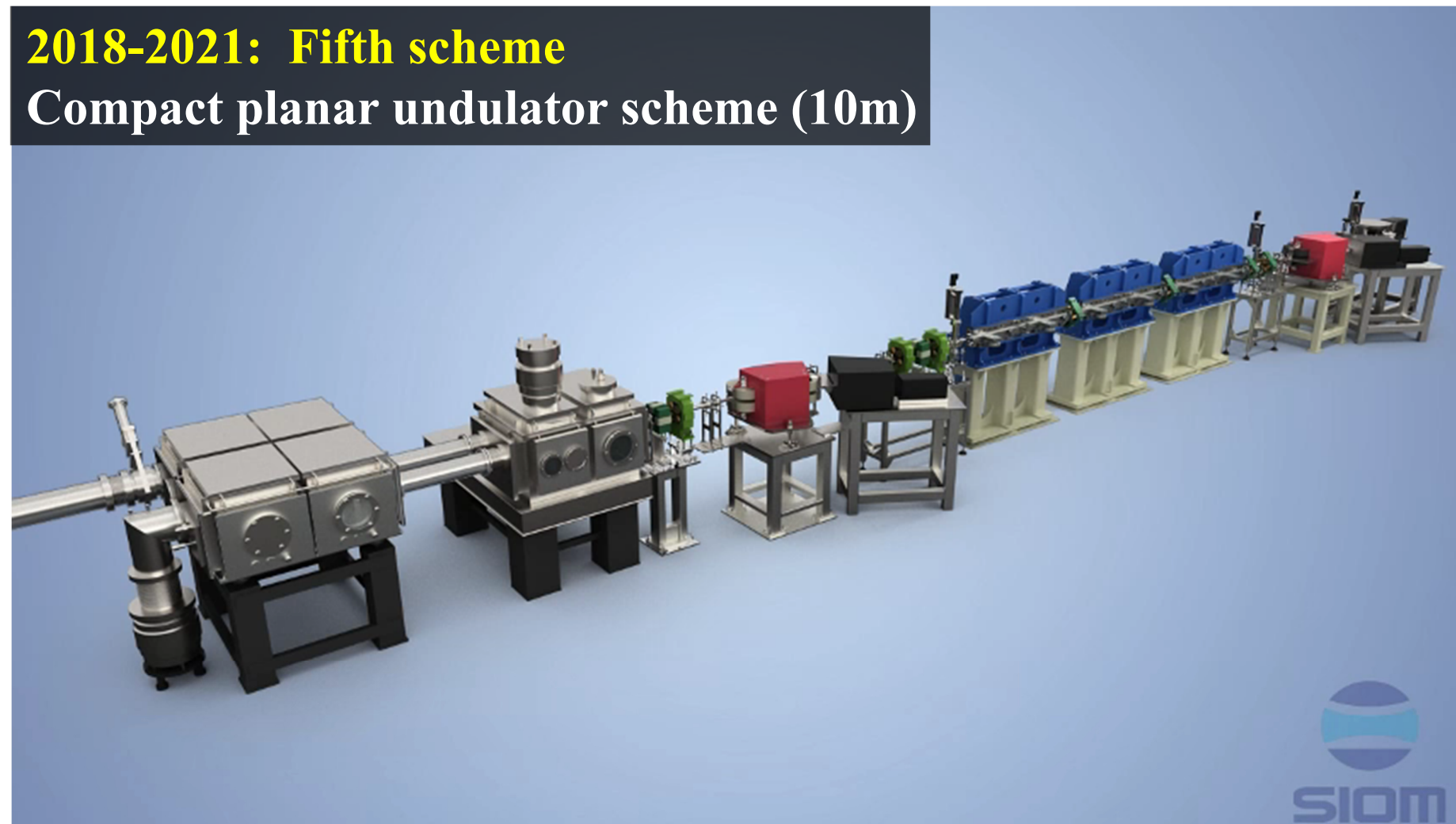


Prof. Chao Feng and Dao Xiang

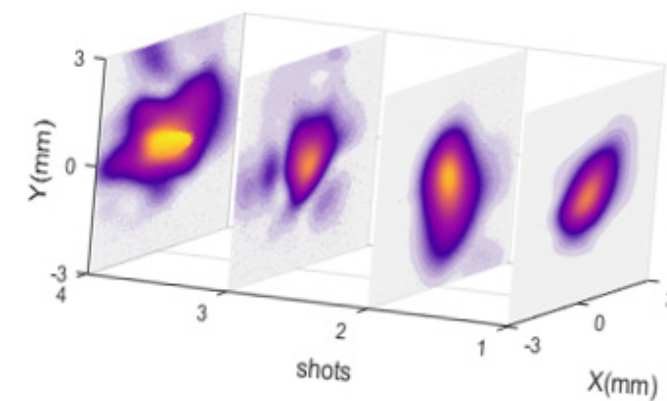
Compact FEL with SASE configuration

2018-2021: Fifth scheme

Compact planar undulator scheme (10m)



Radiation wavelength ~ 27 nm



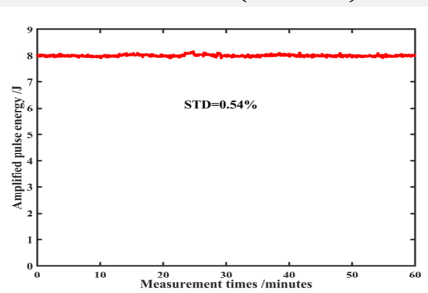
Energy ~ 150 nJ

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

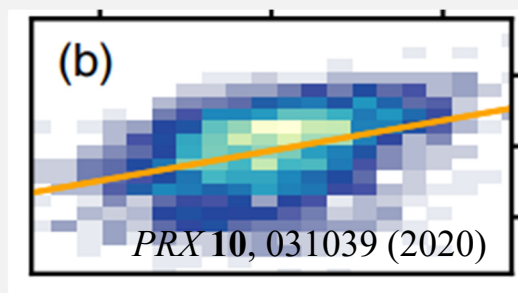
Robustness enhancement for compact FEL system

Considering 3 types of jitter

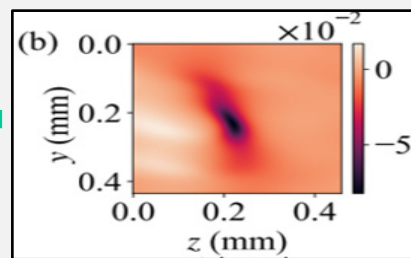
Laser energy jitter
0.54% (RMS)



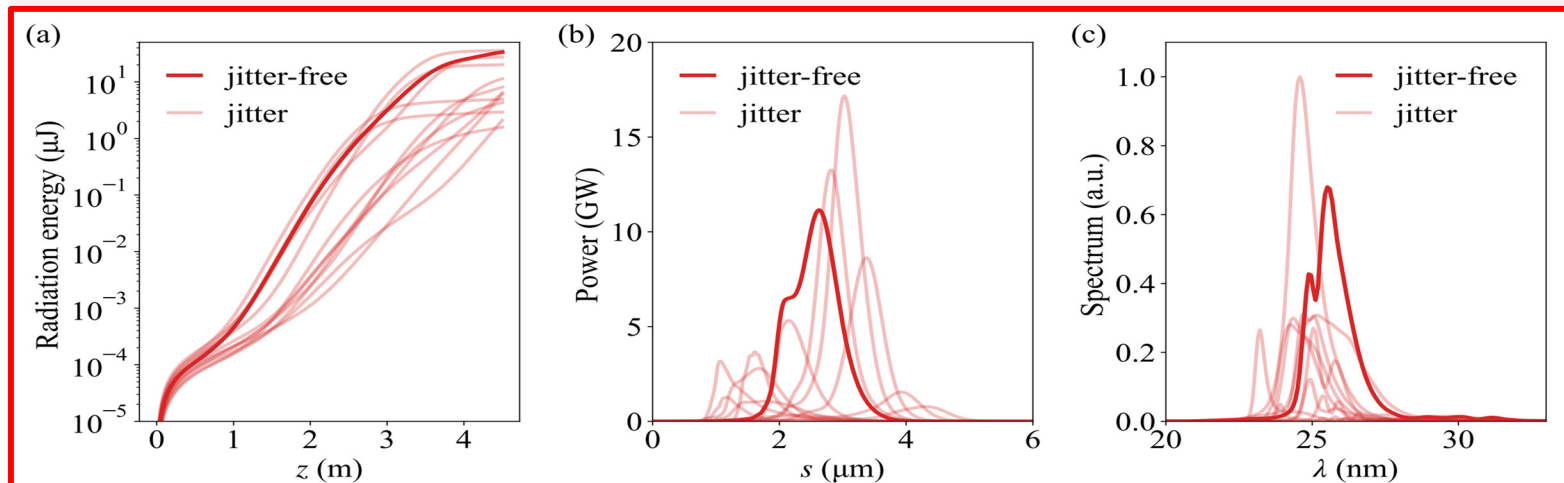
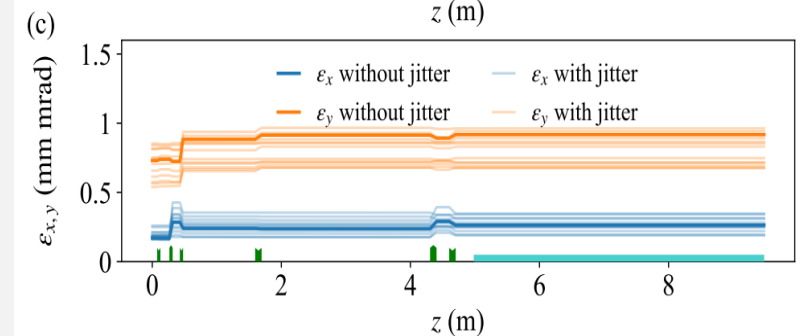
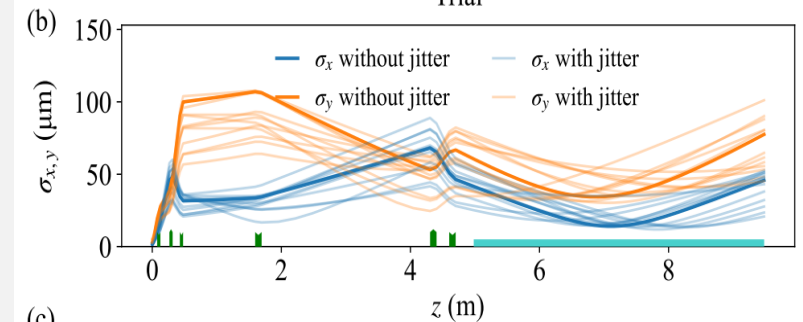
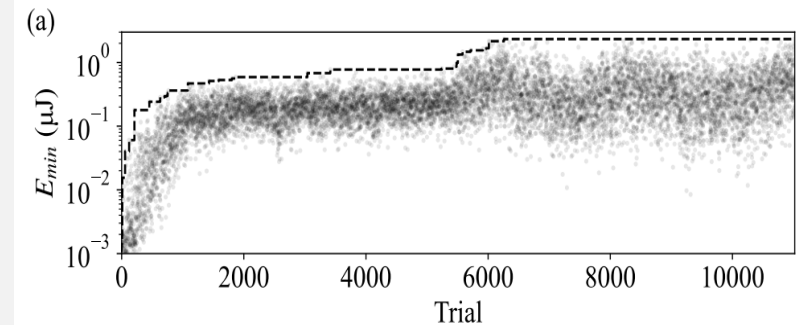
Focus jitter
~200 μm (RMS)



Shock position jitter
~4.9 μm (RMS)

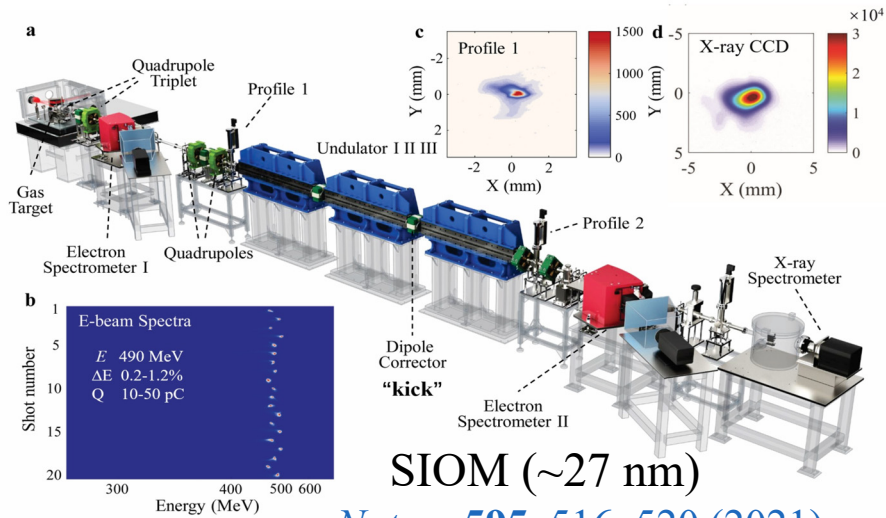


Beamline AI Optimization (13-electron beam ensemble)

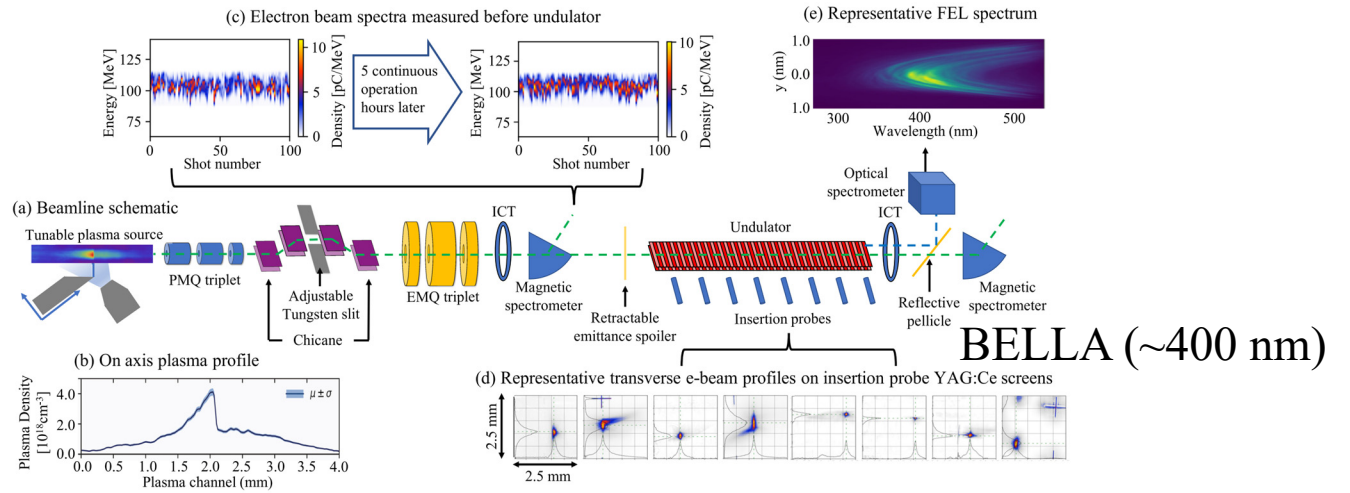


➤ Radiation energy (power) can be maintained **>1 μJ (1 GW)**, even when accounting for twice the root-mean-square (RMS) ranges of experimental inherent jitters.

Compact FELs driven by LWFAs



Nature **595**, 516–520 (2021).



Phys. Rev. Lett. **135**, 055001 (2025).

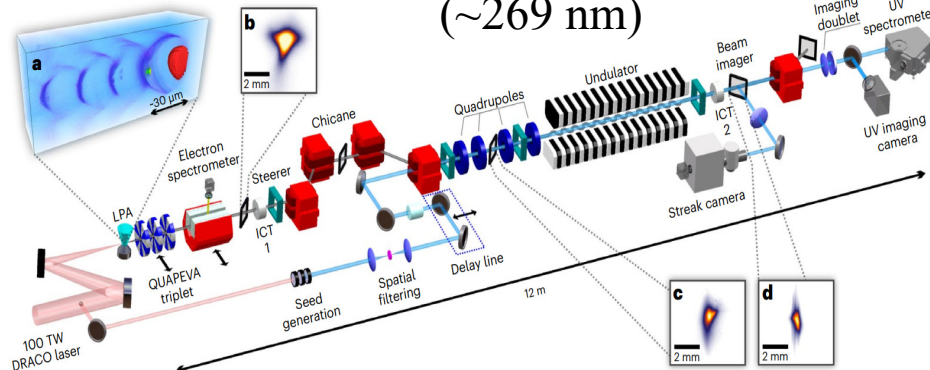
2021

2023

2025

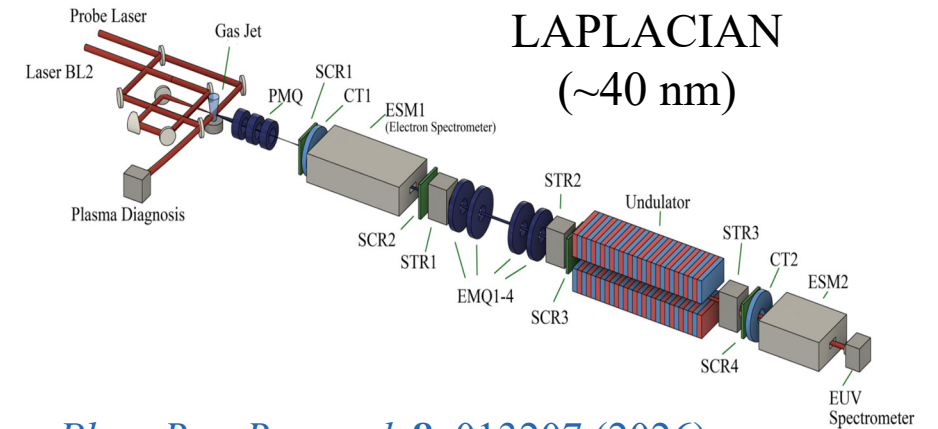
2026

COXINEL–HZDR (~269 nm)



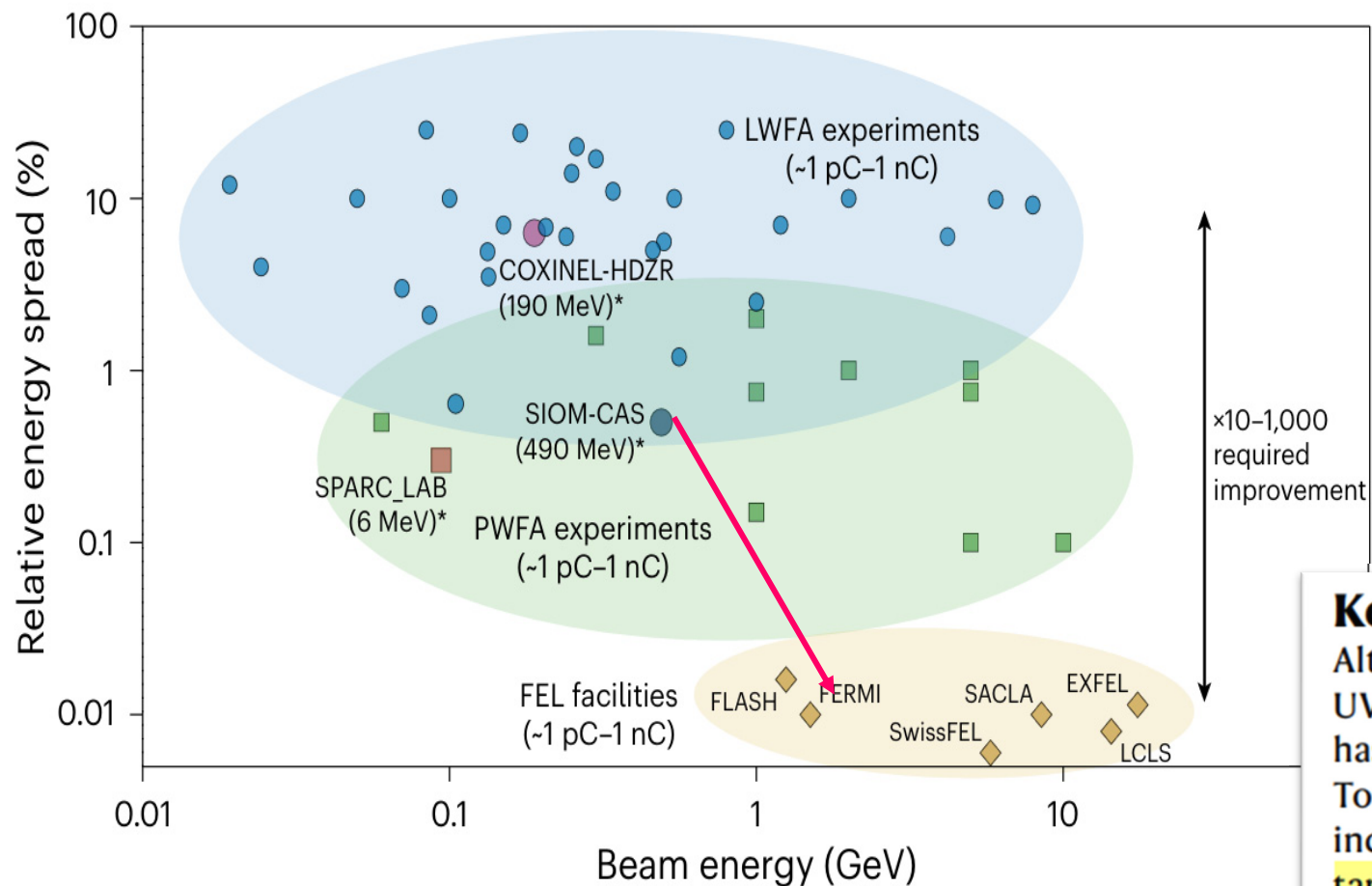
Nat. Photon. **17**, 150–154 (2023).

LAPLACIAN (~40 nm)



Phys. Rev. Research **8**, 013207 (2026).

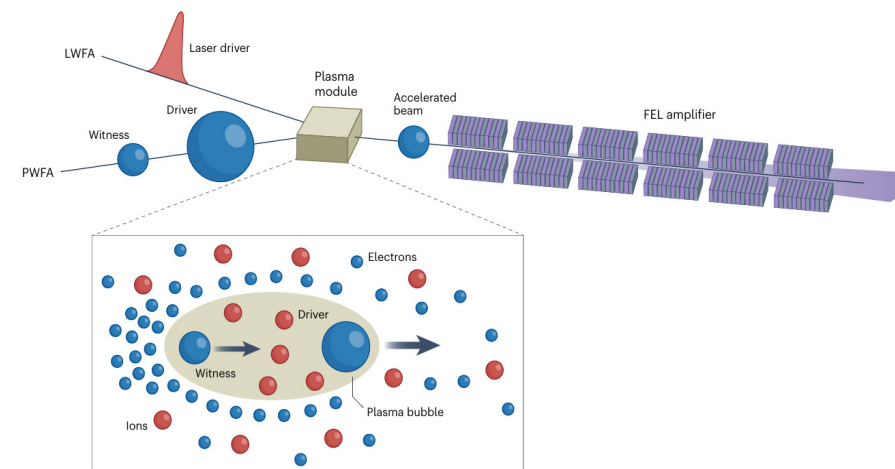
Compact FELs driven by plasma-based accelerator



Ferran Pousa, DOI: [10.3204/PUBDB-2020-04106](https://pubdb-2020-04106).

Dissertation, Universität Hamburg, 2020

There is a **significant gap** between the current **quality of LWFA** and what's needed for a practical FEL.



Eur. Phys. J. Spec. Top. **2020**, *229*, 3675

Key challenges for plasma-based FELs

Although proof-of-principle experiments of plasma-based FELs in the UV and IR range have been conducted, the performance of these FELs has not yet matched those provided by conventional linac-driven FELs. To reduce this gap, it is necessary to address the main open challenges: **increasing the beam energy and brightness**, **reducing the beam emittances and energy spread**, and **increasing the beam repetition rate and average power**. Last but not least, achieving **stable and reliable operation** with an up-time of the order of 90%, as provided by conventional accelerator-based FELs.

Nature Photonics 18, 780–791 (2024).

C2FEL: China Compact Free-Electron Laser



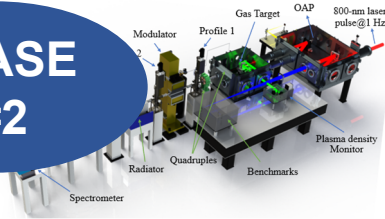
PHASE #1



Proof-of-principle

- 200TW/5Hz Laser system
- ~1% energy spread demonstration
- Reproducible LWFAs
- EUV compact lasing (27 nm)
- Beam characterization

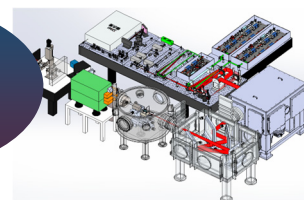
PHASE #2



Technology Breakthrough

- 1PW/0.1Hz Lasers
- ~0.2% energy spread demonstration
- Pre-bunching & superradiation
- Soft X-ray demonstration
- Advanced diagnostics development
- Robust plasma elements

PHASE #3



Prototype Development

- 100TW/100Hz
- Integrated prototype beamline
- Multi-wavelength FEL operation
- AI-enhanced control system

PHASE #4

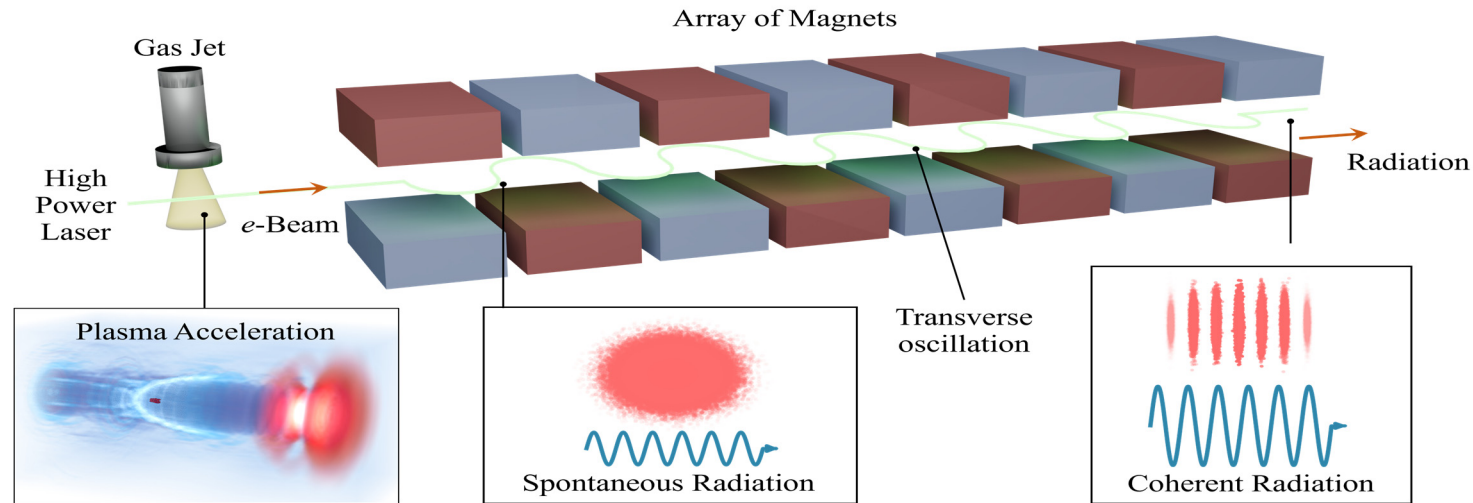


Application Research

- 1PW/10Hz
- Hard X-ray FEL demonstration
- Scientific application programs
- User facility establishment

Compact FEL driven by LWFA

Two different paths for compact FELs



Diagnostic techniques closed-loop feedback system



SASE FEL: Higher energy/power

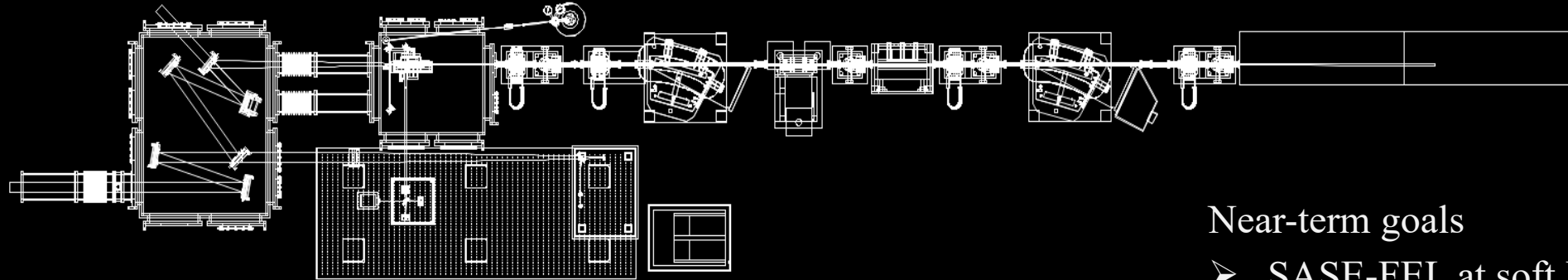
- **Higher Quality** (0.1% energy spread)
- **Higher Stability** (Close to RF accelerators)
- **Higher Energy** (Hard X-ray FEL)

Super-radiance: More Compact

- **Higher Current** (100 kA~1 MA)
- **Higher efficient pre-bunching** (~nm)
- **Higher Stability** (Close to RF accelerators)

New beam line is applicable to both SASE and Pre-bunching FEL

Super-radiance and SASE FEL Beamline with Insert Element



We tried our best to monitor every parameters in the LWFA.

Near-term goals

- SASE-FEL at soft X-ray regime;
- Super-radiance FEL at EUV regime;

Trigger



- Single Trig.
- Repetitive Trig.

Data Collector



- Beam Energy Spectrometer
- BPM
- Motor Position
- Gas Gauge
- CCD

Data Processor



- Target Position/State
- Magnet State
- Electron Beam Parameters

Bayesian Model



- Model Optimiser
- Model Adapter
- Policy Validation

Controller



- Motor
- Gas Valve
- Electromagnet

- The **Bayesian optimization** can be completed automatically based on the electron beam parameters you input.
- The speed optimization depends on the stability and repetition of LWFA.

Collaborations and Acknowledgement



Shanghai Advanced Research Institute

Zhentang Zhao, Chao Feng, Bo Liu,
Haixiao Deng, Tao Liu, Luyang Yu, Dong
Wang, Wei Zhang, Hao Guo...



China Academy of Engineering Physics

Zongqing Zhao, Yuchi Wu, Weimin Zhou,
Yuqiu Gu, Feng Zhang, Zhigang Deng, Shaoyi
Wang, Jiaxing Wen...



SLAC Faculty

Zhirong Huang



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Linmin Chen, Xulei Ge...



China Academy of Engineering Physics

Min Li, Yuqiao Zhang, Kai Zhou...
Liangwen Chen, Li Deng...



Peking University

Xueqing Yan, Xinlu Xu, Chen Lin...



University of Science and Technology of China

Yin Shi, Zhigang He, Zhenghe Bai,
Guangyao Feng, Ziwen Pan...



Shanghai Normal University

Jiansheng Liu, Changhai Yu, Zhiyong Qin...

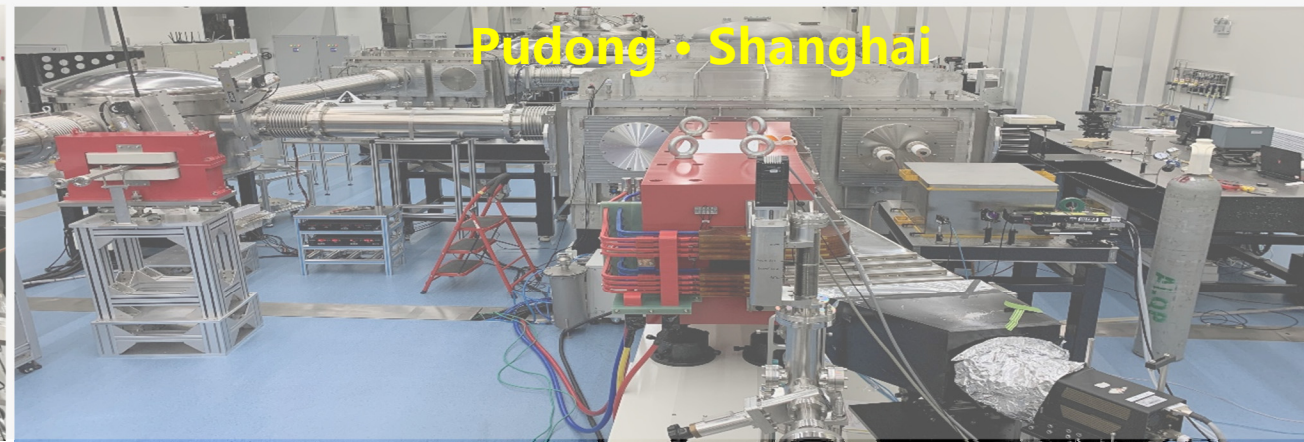


Institute of High Energy Physics

Dazhang Li, Ming Zeng, Chen Wu, Yantao Liu

Thanks the entire laser-plasma community for their inspiration and support!

Collaborations and Acknowledgement



Prof. Ruxin Li



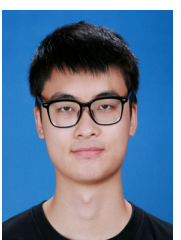
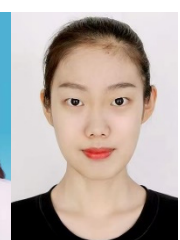
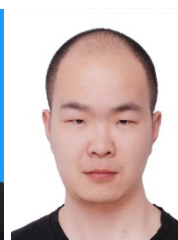
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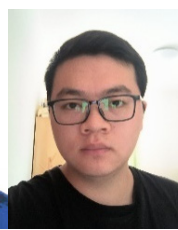
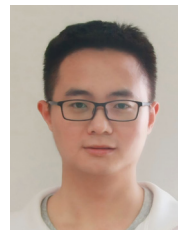


Laser: Yuxin Leng, Yi Xu



**Simulations
Dr. Jia Wang**

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Collaborations and Acknowledgement

- Thanks the European Physical Society, its Accelerator Group and the IPAC'26 Prize Committee.

Thanks the Nominators



Prof. Xueqing Yan
Peking University



Prof. Victor Malka
Weizmann Institute of Science
Scientific Director of ELI NP



Prof. Ruxin Li
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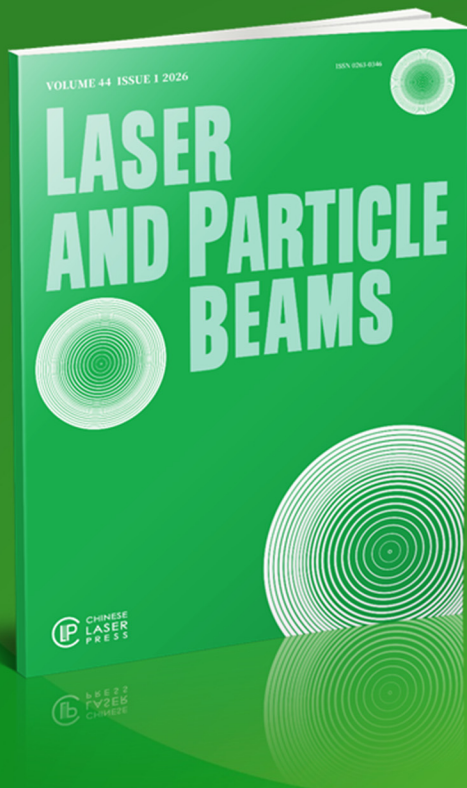


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