High-quality electron beams and free electron lasing based on a laser wakefield accelerator at SIOM

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Outlines

1. Background and motivations
2. Major progress in developing high-quality laser wakefield accelerators (LWFAs) at SIOM
3. Table-top free electron lasing based on a laser wakefield accelerator
4. Summary

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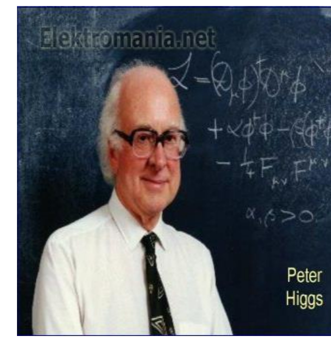
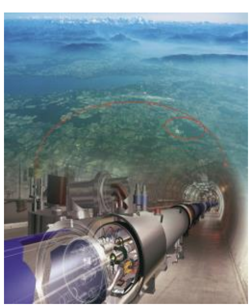
Background and motivations

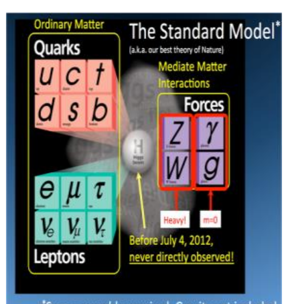
More than half of the Nobel prizes in Physics (60/113) have been related to particle acceleration and its applications since the last century.

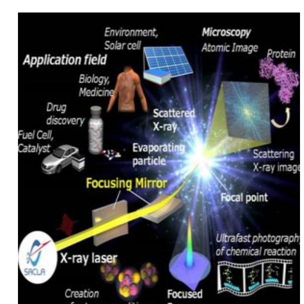
- ●Higgs (Higgs et al)
- ●Meson (L Lederman et al)
- ●J/ψ (Samuel C. C. Ting et al)
- ●Nucleus strucuture (R Hofstadter)
- ●Antiproton (E Segrè and O Chamberlain)
- ●Particle acceleration (J Cockcroft)
- ●Artificial radioactivity (F Lorence)
- ●Slow neutron (Fermi)
- ●Neutron (Chadwick)
- ●Nucleus (Rutherford)
- ●Proton (Rutherford)
- ●Electron (Thomson)



1900 1920 1940 1960 1980 2000 2020 2030





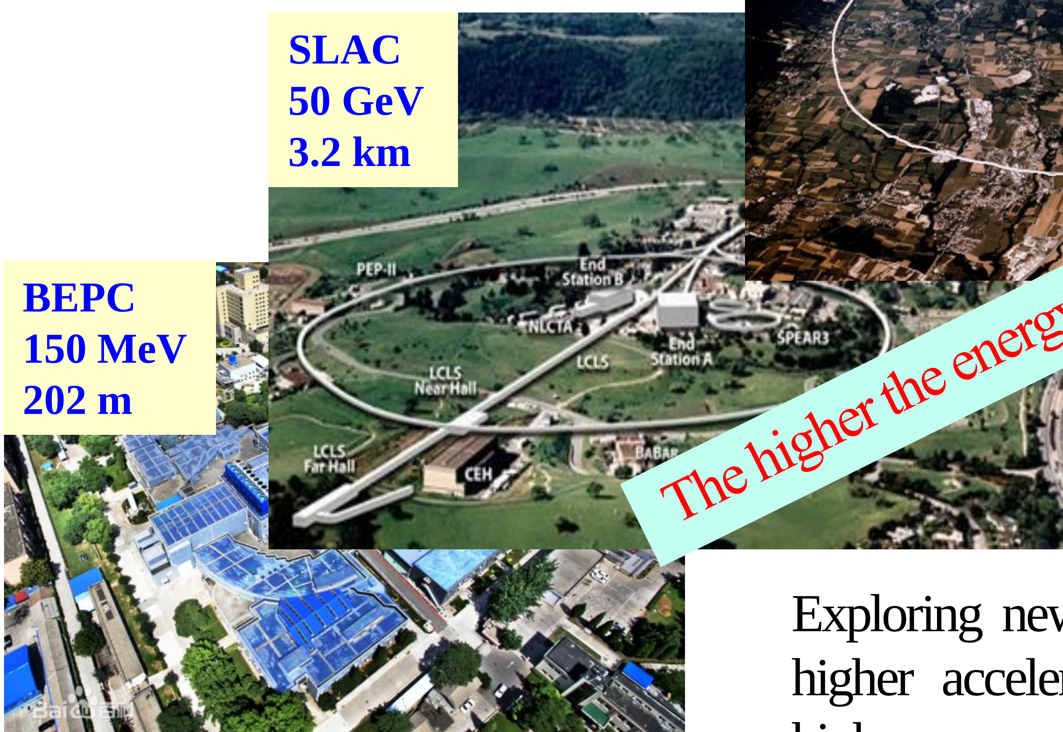


Challenges

Energy ∝ accelerating fields × accelerating length

Accelerating gradient:

E< 100 MV/m



Exploring new acceleration mechanism with much higher accelerating gradient is the only way for higher-energy particle beam and compact accelerator.

LWFA: a new compact accelerator

The LWFA was proposed in 1979!

T. Tajima **J.M. Dawson**

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

Laser field
Transverse field

plasma

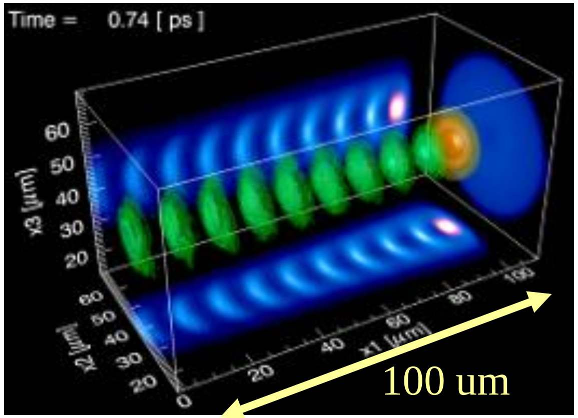
Without breakdown voltage

Plasma wakefield
Longitudinal field

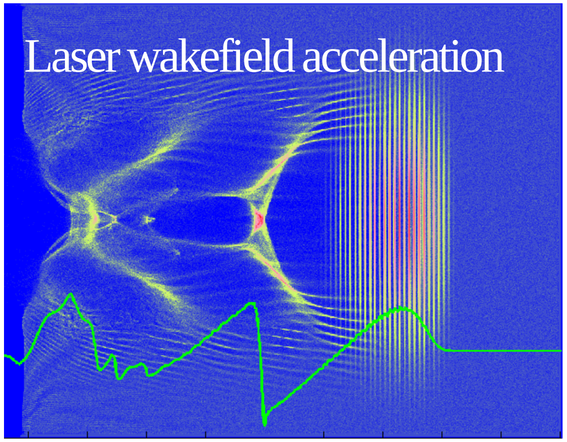
Accelerating gradient~**100MV/m**

Radiofrequency cavity (1 m-long)

Accelerating gradient~**100GV/m**



3D PIC simulation of a plasma wave (UCLA)



Beam energy enhancement in LWFA

In 1985, CPA was invented and used to excited large-amplitude wakefield!

In 1995, the ultra-high accelerating gradient was observed experimentally!

VOLUME 74, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 1995

Observation of Ultrahigh Gradient Electron Acceleration by a Self-Modulated Intense Short Laser Pulse

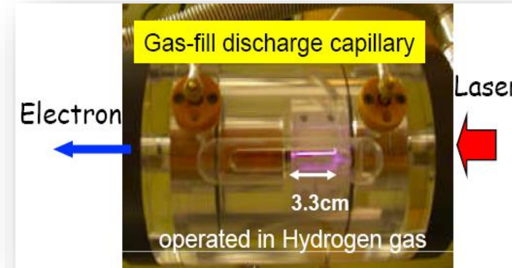
K. Nakajima,[1] D. Fisher,[5] T. Kawakubo,[1] H. Nakanishi,[1] A. Ogata,[1] Y. Kato,[2] Y. Kitagawa,[2] R. Kodama,[2] K. Mima,[2] H. Shiraga,[2] K. Suzuki,[2] K. Yamakawa,[2] T. Zhang,[2] Y. Sakawa,[3] T. Shoji,[3] Y. Nishida,[4] N. Yugami,[4] M. Downer,[5] and T. Tajima[1]
[1]*National Laboratory for High Energy Physics, Tsukuba, Ibaraki, Japan*
[2]*Institute of Laser Engineering, Osaka University, Osaka, Japan*
[3]*Plasma Science Center of Nagoya University, Nagoya, Japan*
[4]*Utsunomiya University, Utsunomiya, Japan*
[5]*The University of Texas at Austin, Austin, Texas 78712*
(Received 25 July 1994)

A laser pulse with a power of ~3 TW and a duration of 1 ps has been focused onto a gas. Ultrahigh-gradient electron acceleration has been observed in the laser-produced plasma with a density of ~10^{19} cm^{-3} when injecting 1 MeV/c electrons. The simulation of the laser-plasma interaction revealed the existence of ultrahigh-gradient wake fields excited due to self-modulation of the laser pulse and its electron acceleration, consistent with the experimental results.

PACS numbers: 29.17.+w, 52.35.Mw, 52.40.Nk, 52.65.−y

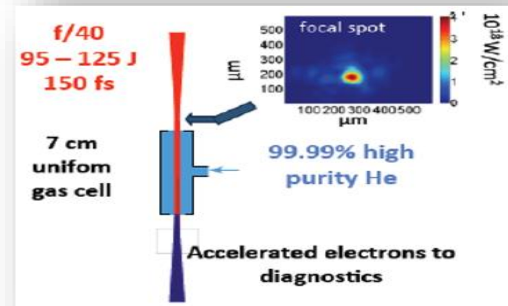
2006, 3.3-cm gas filled discharge capillary, **1 GeV**

Nature Physics, 2, 696(2006)



2013, 7.0-cm gas filled discharge capillary, **2.3 GeV**

Nature Comm. 4, 1988 (2013)



2014, 9.0-cm gas filled discharge capillary, **4.3 GeV**

Phys. Rev. Lett. 113, 245002 (2014)

APS physics

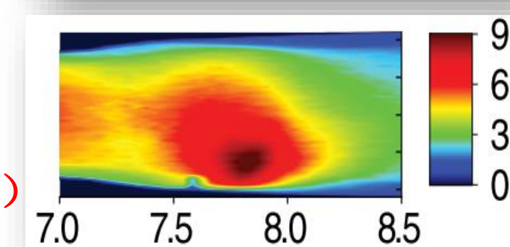
Top Ten Physics News Stories in 2014

Tabletop Accelerator

In **December**, scientists at Lawrence Berkeley National Lab announced a new world record for a compact particle accelerator. The team used a tabletop-sized laser-plasma accelerator to energize electrons up to 4.25 GeV. Though

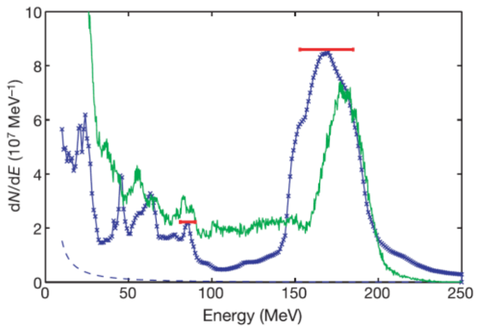
2019, 20-cm gas filled discharge capillary, **7.8 GeV**

Phys. Rev. Lett. 122, 084801 (2019)



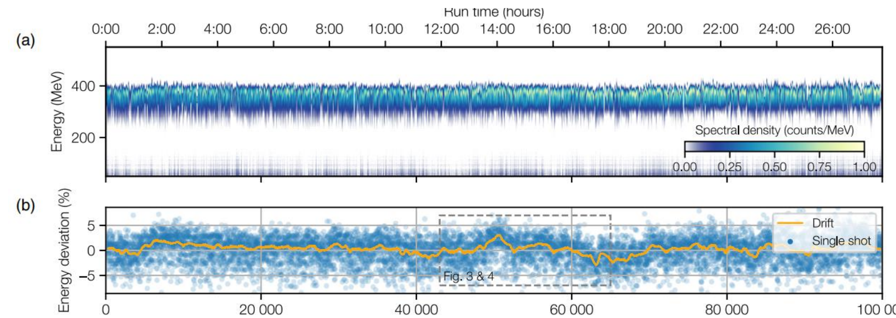
Beam quality improvement in LWFAs

In 2004, the first generation of quasi-monoenergetic electron beam.



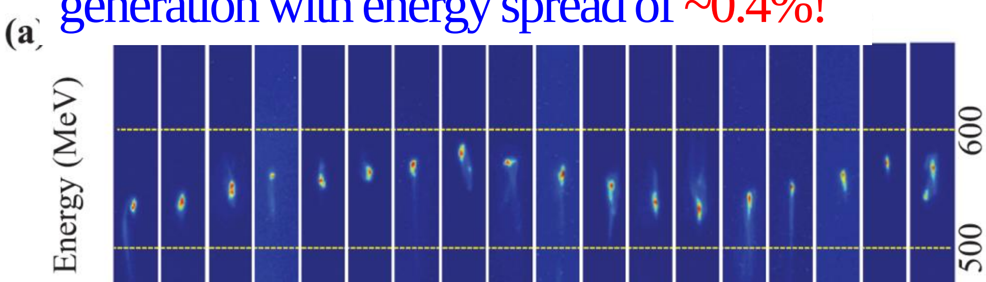
Nature, 431, 541 (2004)
Nature, 431, 535 (2004)
Nature, 431, 538 (2004)

In 2020, 100 000 consecutive electron beam generation in the 24-h stable operation.



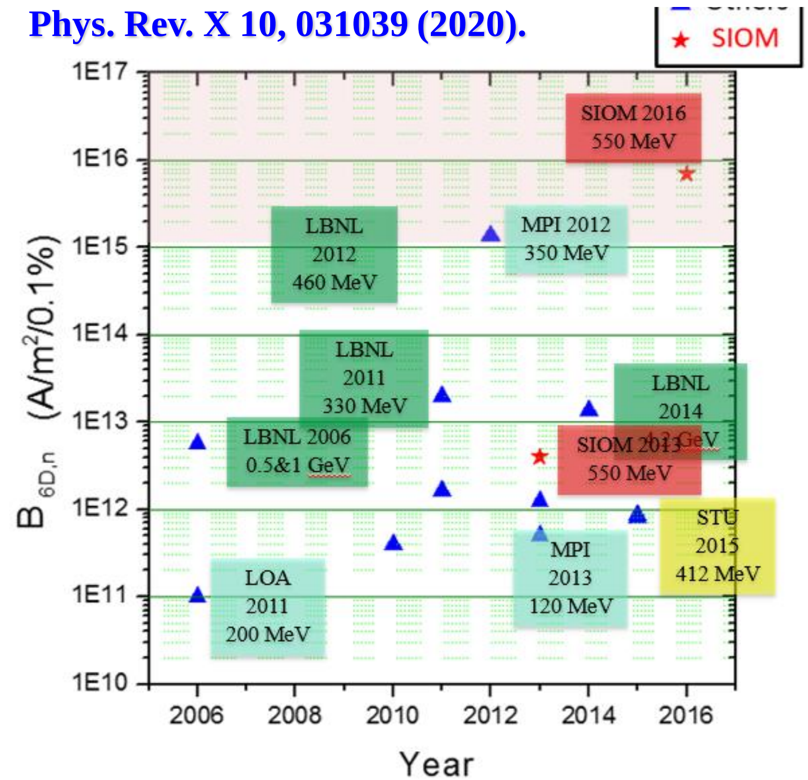
Phys. Rev. X 10, 031039 (2020).

In 2016, high-brightness electron beam generation with energy spread of ~0.4%!



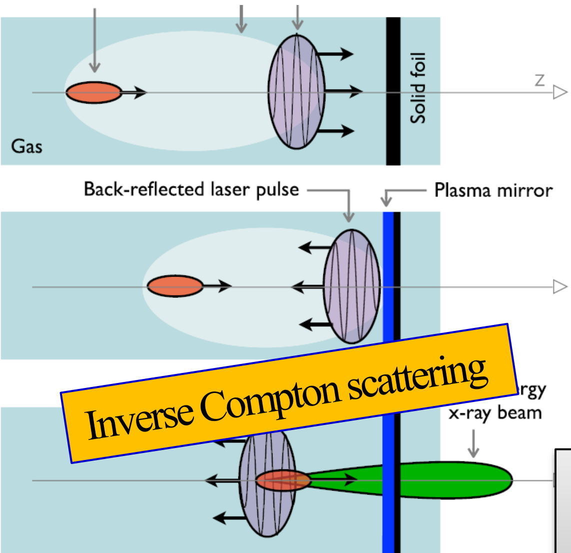
$\Delta E/E$ (%)	0.7	1.0	1.2	0.5	0.8	0.9	1.0	1.2	0.5	0.7	1.0	1.0	1.2	1.1	0.4	0.9	0.8	1.1
Q (pC)	28	22	30	10	26	42	27	37	25	15	70	40	37	13	22	10	25	50
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

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

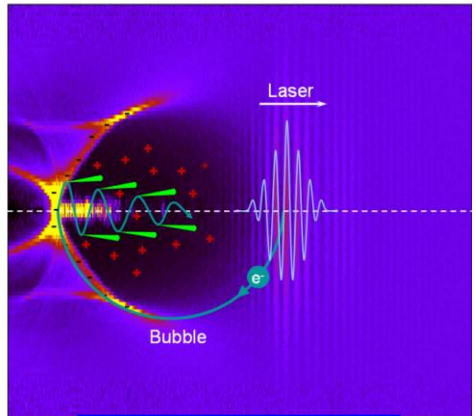


New opportunities for compact radiation sources

Nat. Photon.**6**, 308 (2012)

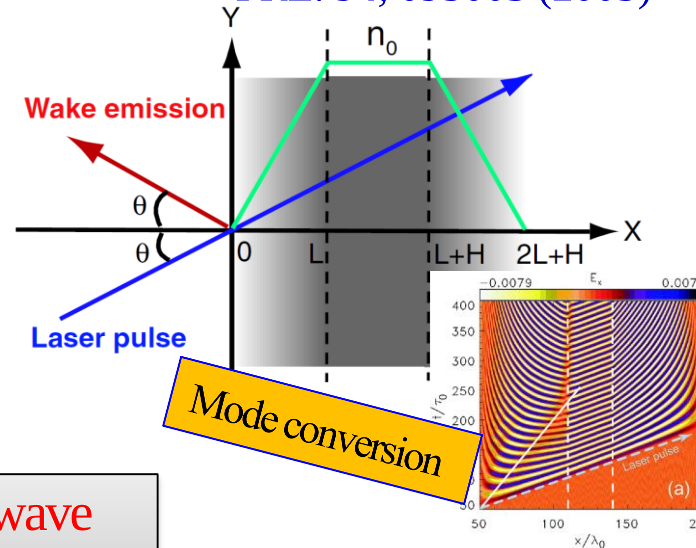


Inverse Compton scattering



Betatron radiation

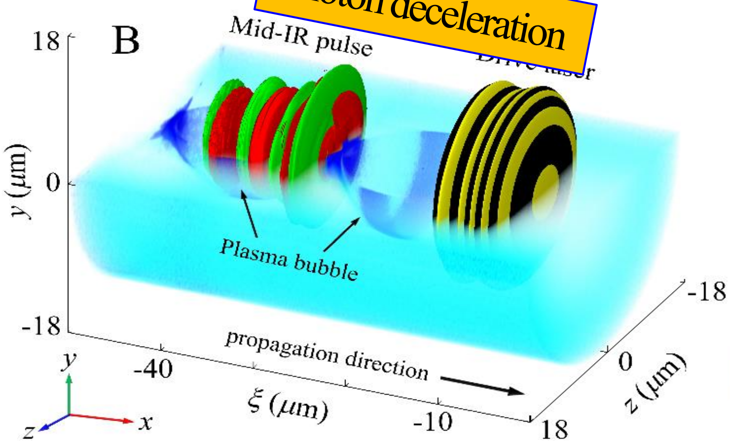
PRL. **94**, 095003 (2005)



Mode conversion

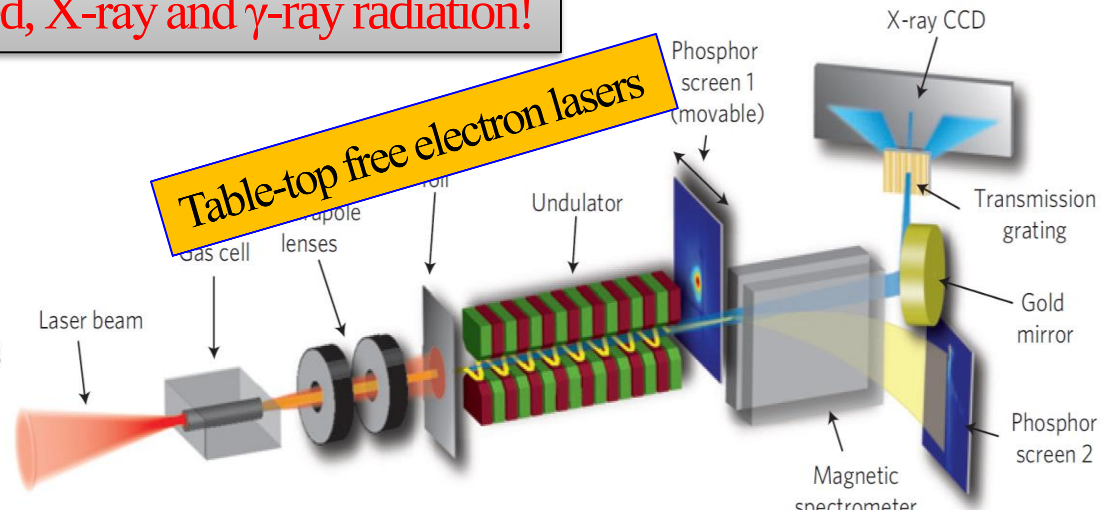
Realize compact and full wave band coverage of strong THz, Mid-infrared, X-ray and γ-ray radiation!

Photon deceleration



Nat. Photon.**12**, 489 (2018)

Table-top free electron lasers

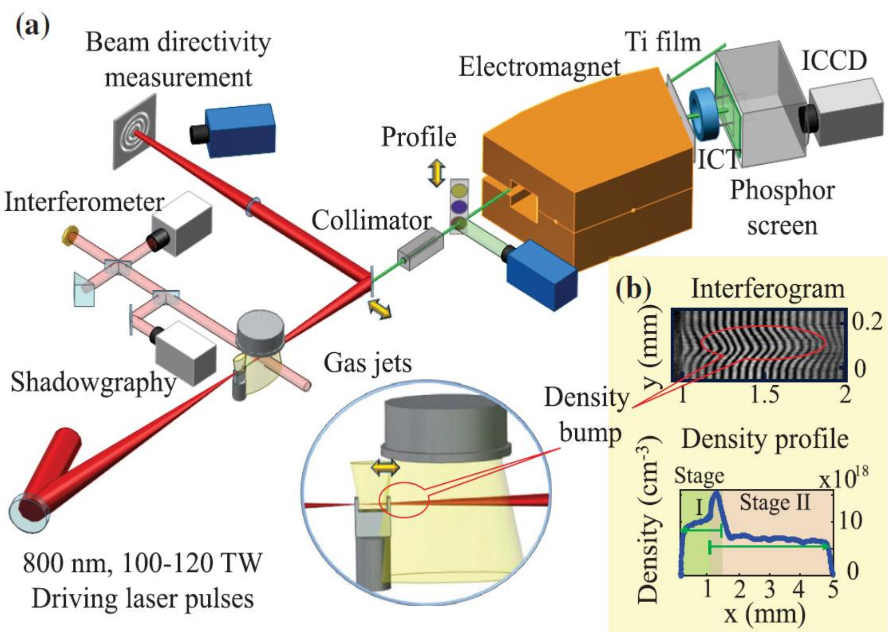


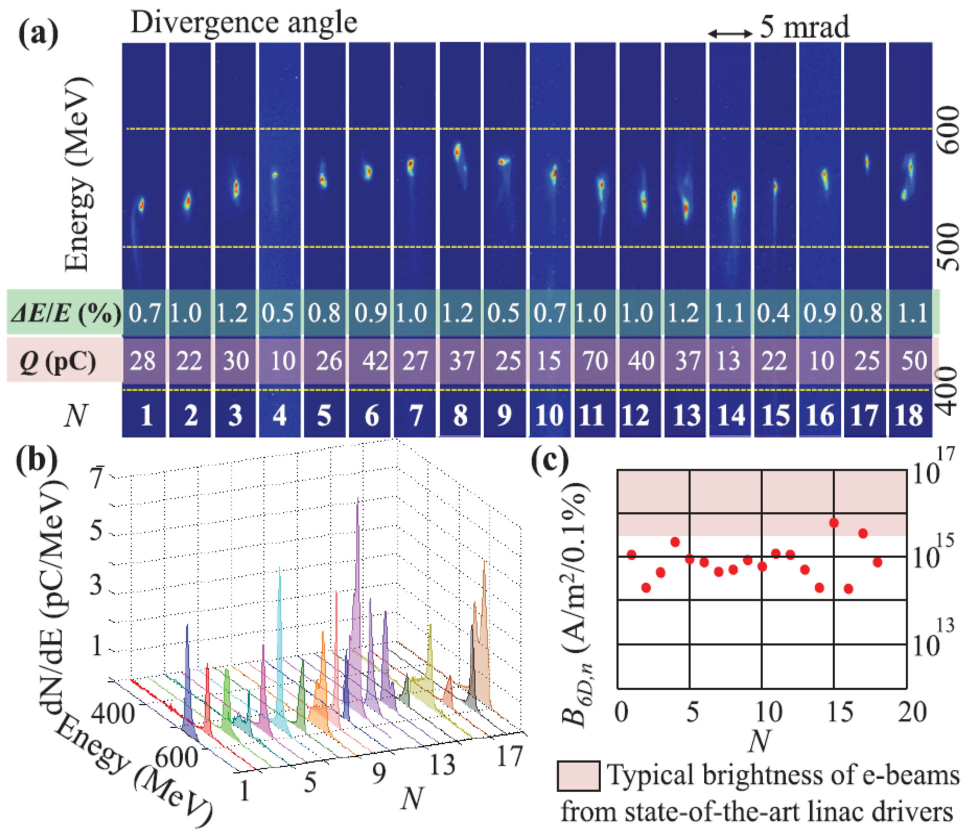
Nat. Phys. **5**, 826 (2009)

Outlines

1. **Background and motivations**
2. **Major progress in developing high-quality laser wakefield accelerators (LWFAs) at SIOM**
    - **High-brightness *e* beam generation**
    - **Stability improvement and stable *e* beam generation**
    - **Near-GeV, 2‰-level *e* beam generation**
3. **Table-top free electron lasing based on a laser wakefield accelerator**
4. **Summary**

High brightness *e* beam generation





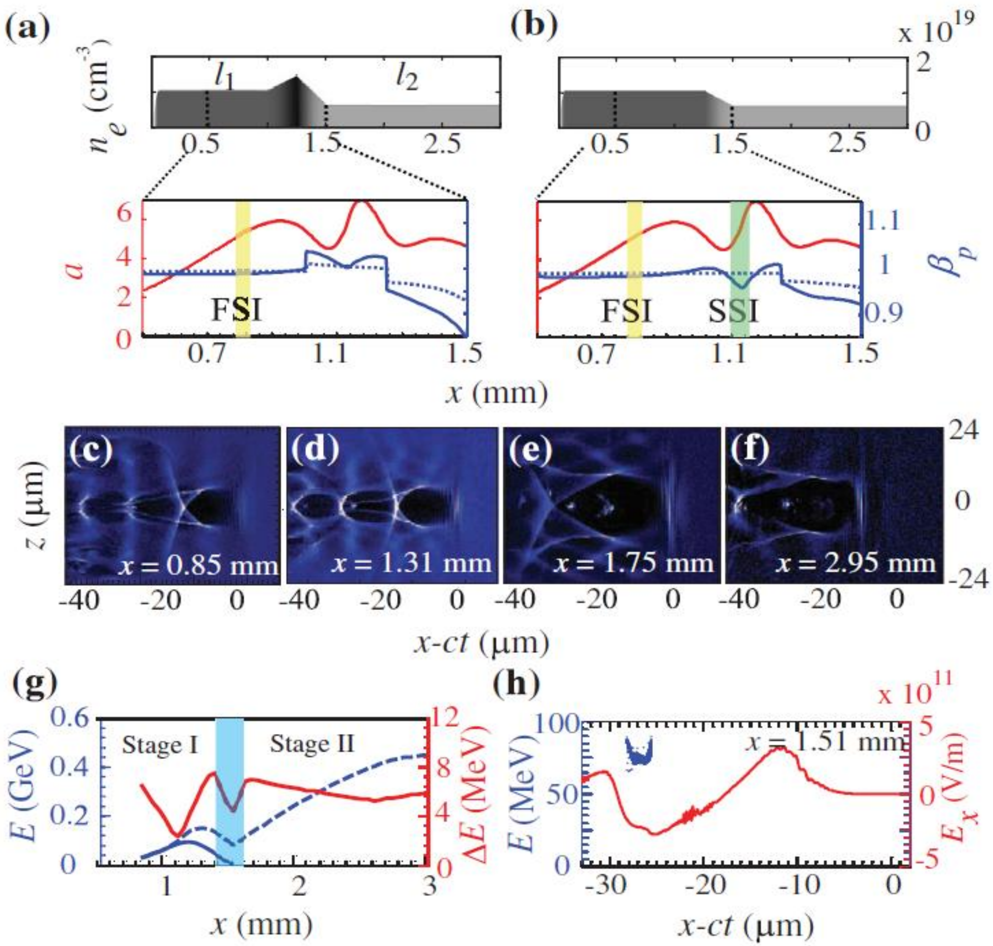
The all-round properties of *e* beams is estimated by 6D brightness:

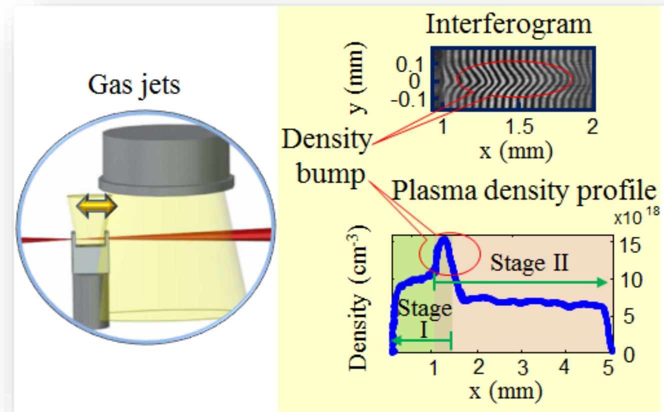
$$B_{6D} = \frac{I_p \cdot 0.1\%}{\varepsilon_{nx}\varepsilon_{ny}\sigma_{\gamma}}$$

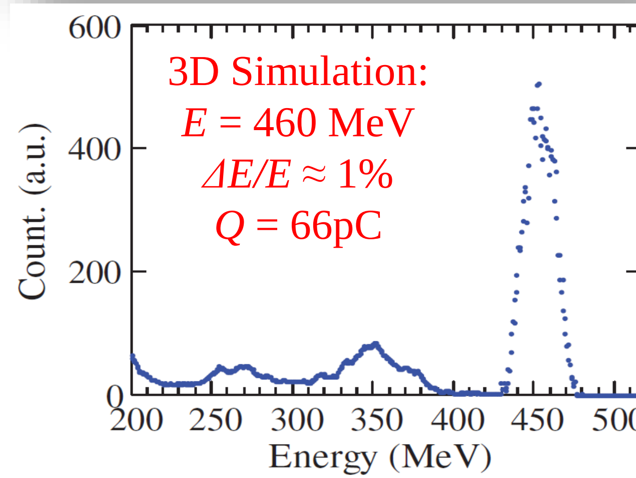
Phys. Rev. Lett. 117, 124801(2016) .

- **High-quality *e* beam was experimentally generated (peak energy of 200-600 MeV, rms energy spread of 0.4%-1.2%, charge of 10-80 pC and rms divergence of ~0.2 mrad).**
- **The maximum 6D brightness is estimated as ~6.5×10^{15} A/m²/0.1%, which is close to the typical brightness of *e* beam from state-of-the-art linac drivers.**

High brightness *e* beam generation



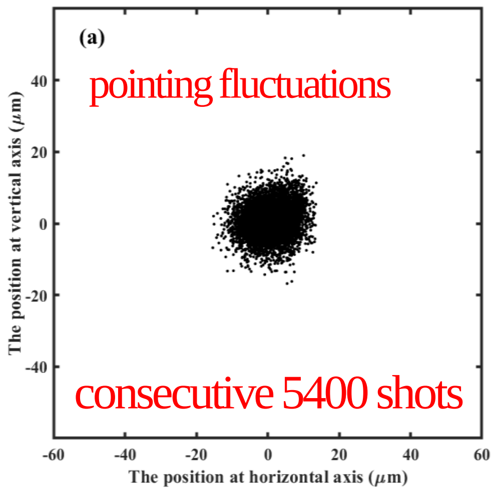


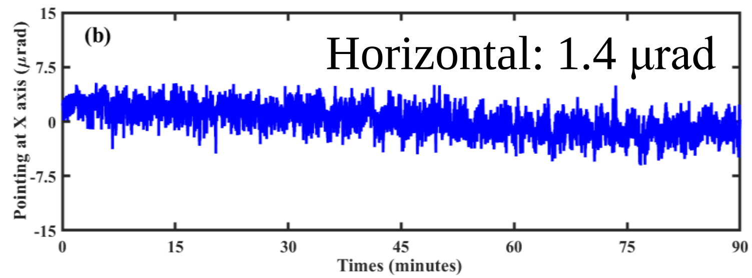


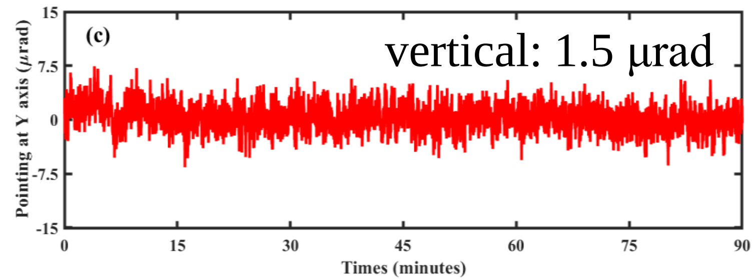
Phys. Rev. Lett. 117, 124801(2016) .

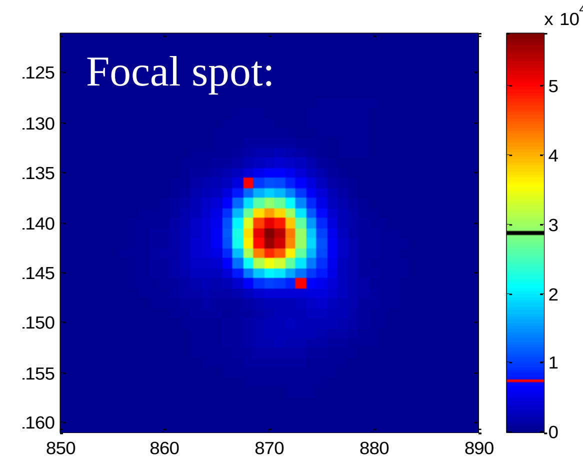
- By constructing a density bump between the two-segment plasmas, the second electron injection could be prohibited;
- The e beam experienced a segment of negative-slope wakefield in the downward density ramp and the energy chirp can be reversed.

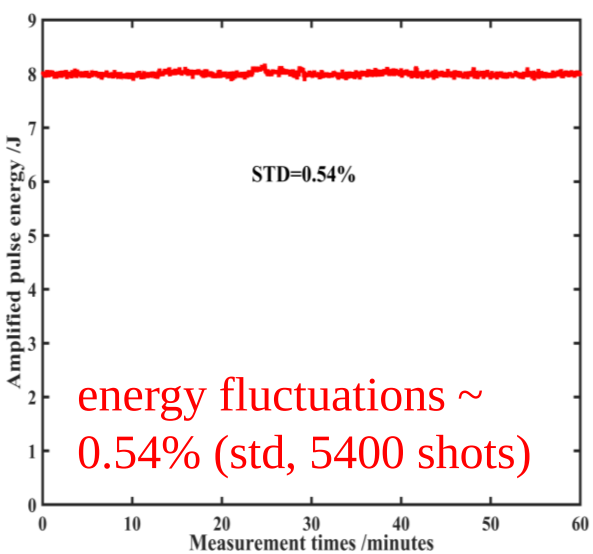
Stability improvement: self-developed 200-TW laser system



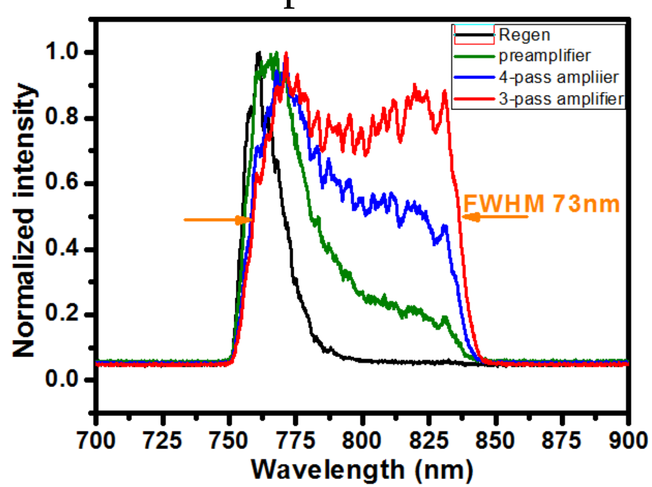








spectrum

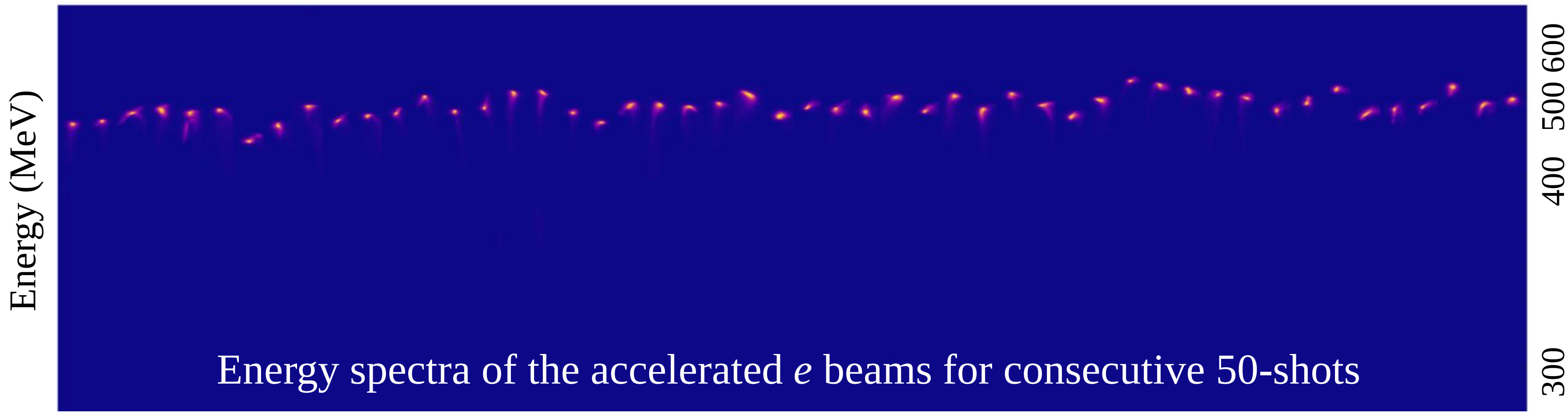


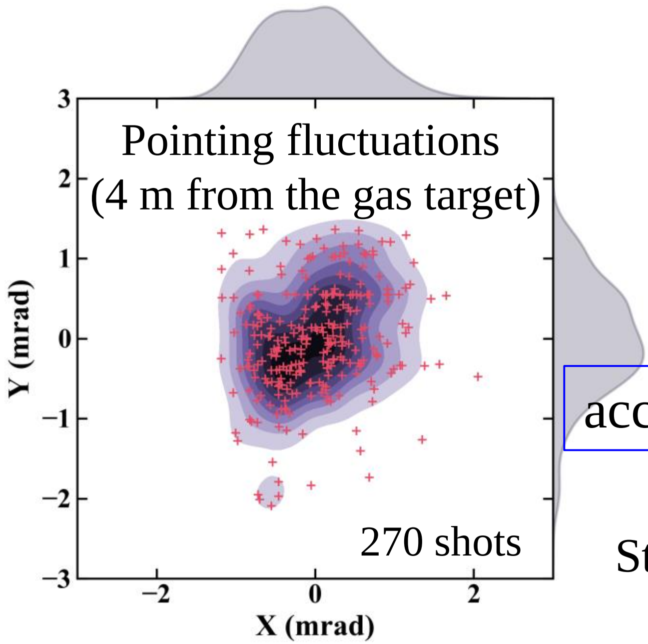
Opt. laser Technol. 131, 106453(2020) .

Performance of 200 TW/1Hz laser system:

- ➢ Pointing stabilities: 1.4μrad / 1.5μrad;
- ➢ Energy stabilities: 8J / 0.54% (std);
- ➢ Beam waist: 37.7 μm (FWHM);
- ➢ Pulse duration: 25 *f*s.
- ➢ Energy concentration: ~28.8 (FWHM)

Stability improvement: Stable *e* beam generation





Reproducibility:
30% ➡ 100%

⇩

acceleration ➡ accelerator?

Still needs our joint efforts!

Laser system

800nm, 30fs, linear polarized

2.9 – 3.6 × 10^{18} W/cm^2 @ target

Spot size (FWHM) ~ 38 μm

Pointing stability (std) < 2μrad

Energy stability (std) ~ 0.54%

Beam properties

Peak energy stabilities (std) < 3%

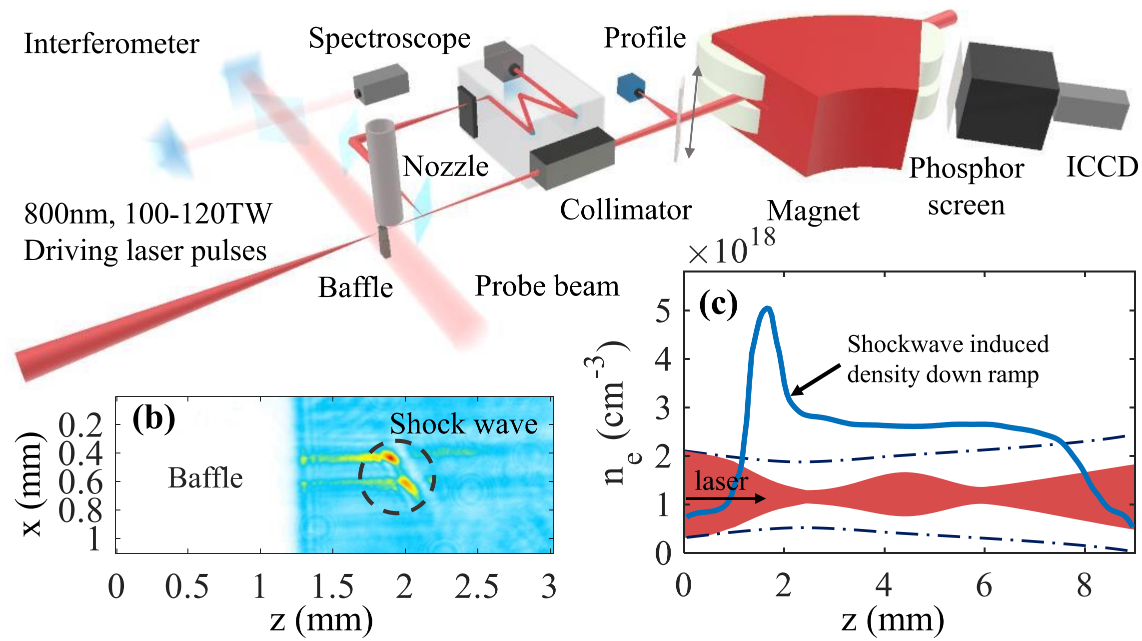
Energy spread ~ 0.2-1.2%

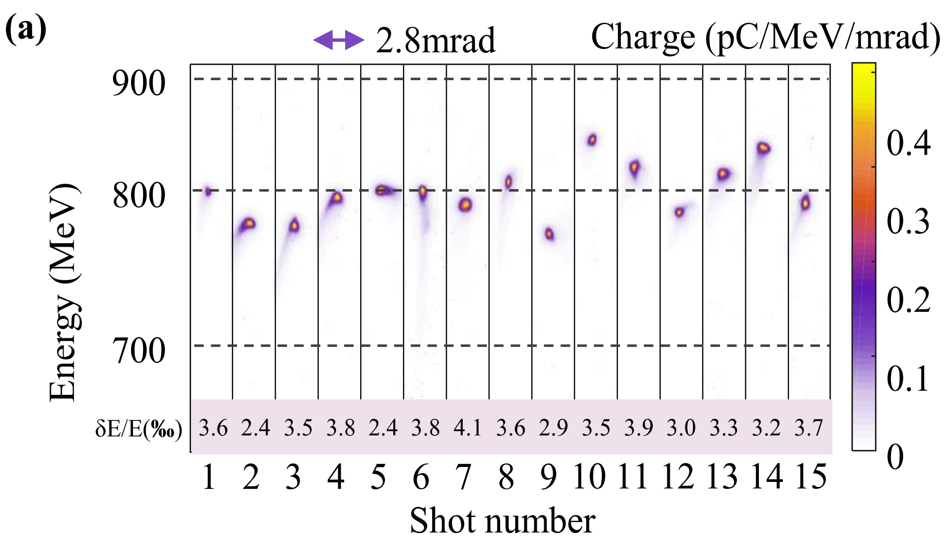
Charge ~ 10-50 pC

Divergence ~ 0.1-0.4 mrad

Pointing stability (std) = 0.6 mrad

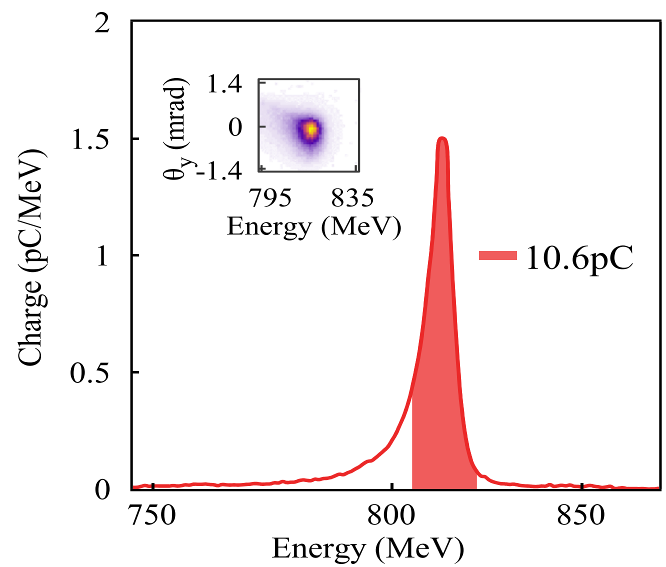
Near-GeV, 2‰-level *e* beam generation





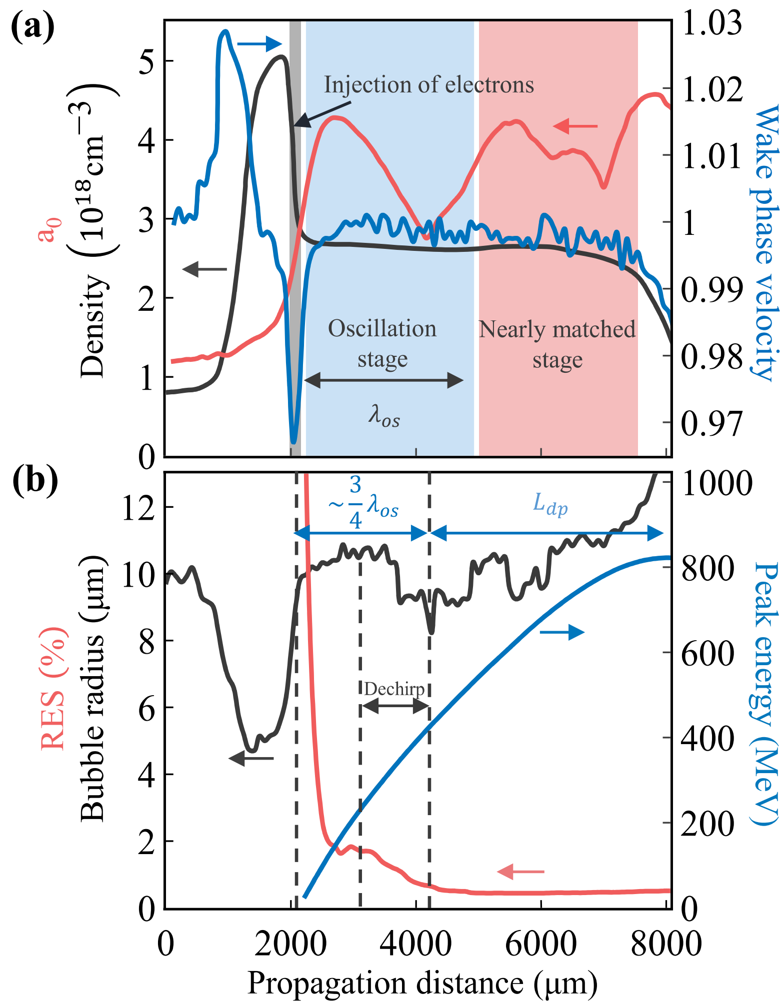
***e*-beam parameter**

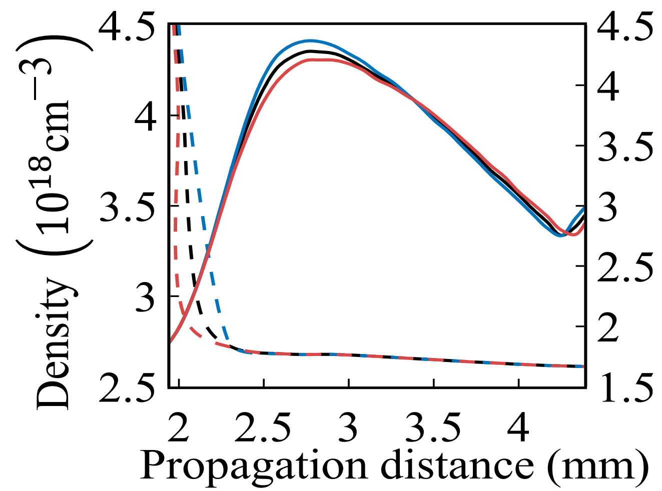
- Peak energy: 780-840 MeV
- RES: **2.4‰-4.1‰**
- Charge: 8.5-23.6 pC
- Divergence: 0.1-0.4 mrad



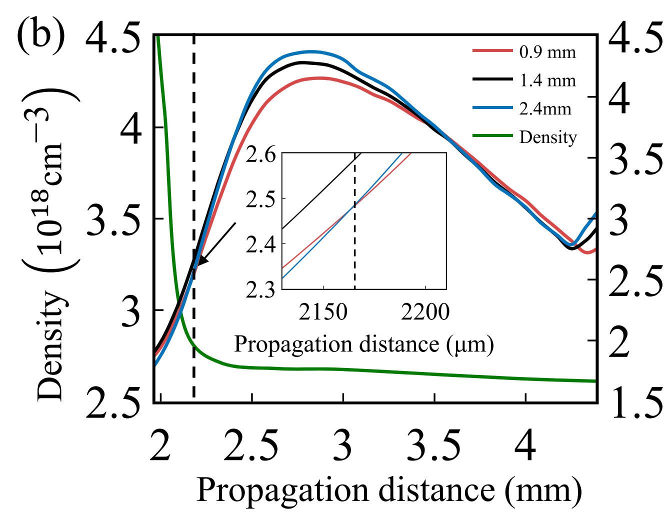
Longitudinal plasma density was tailored to control relativistic laser-beam evolution in a single-stage LWFA. High quality electron beam with energy of ~ 800MeV, energy spread of 2‰ level was experimentally obtained.

Near-GeV, 2‰-level *e* beam generation: synergic injection





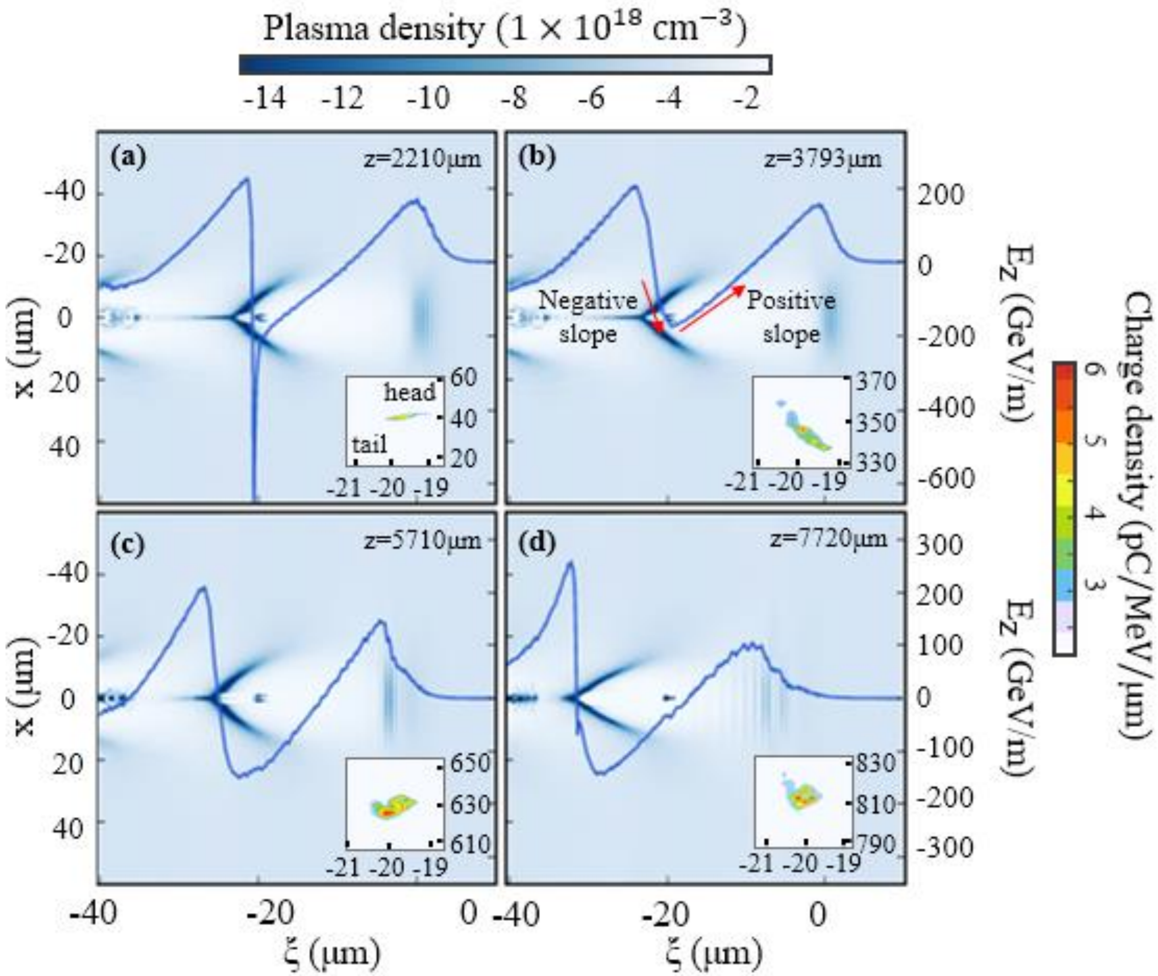
Width of denisty downramp

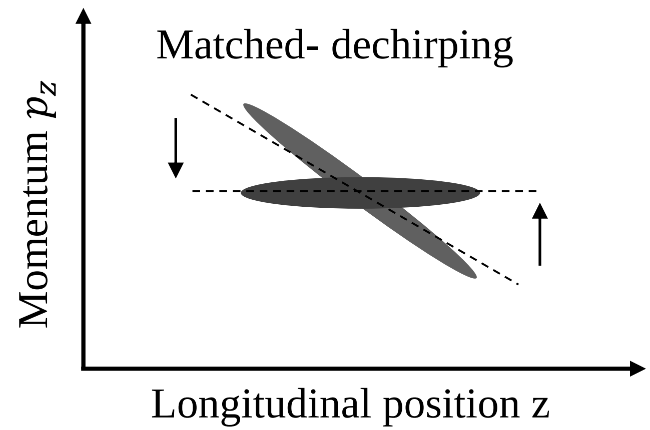


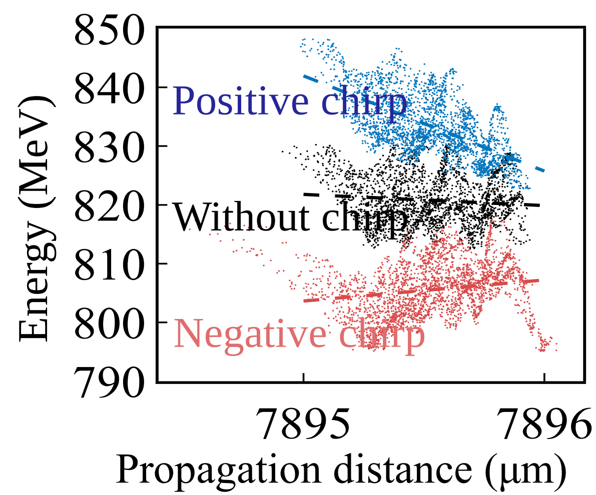
Focal position

- ➢ Electrons were injected at the end of the density downramp and the position of maximum gradient of a_0;
- ➢ The injection of the electrons was manipulated by controlling the density downramp and the evolution of the laser.

Near-GeV, 2‰-level *e* beam generation: chirp compensation







- ➢ The energy spread was compensated due to the evolution of the laser and the beamloading effects.
- ➢ The accelerating gradient was reached to **142 GV/m** on average.
- ➢ The dechirping strength was estimated to reach up to **11 TeV/mm/m**.

L. T. Ke *et al*, Phys. Rev. Lett. 126, 214801(2021).

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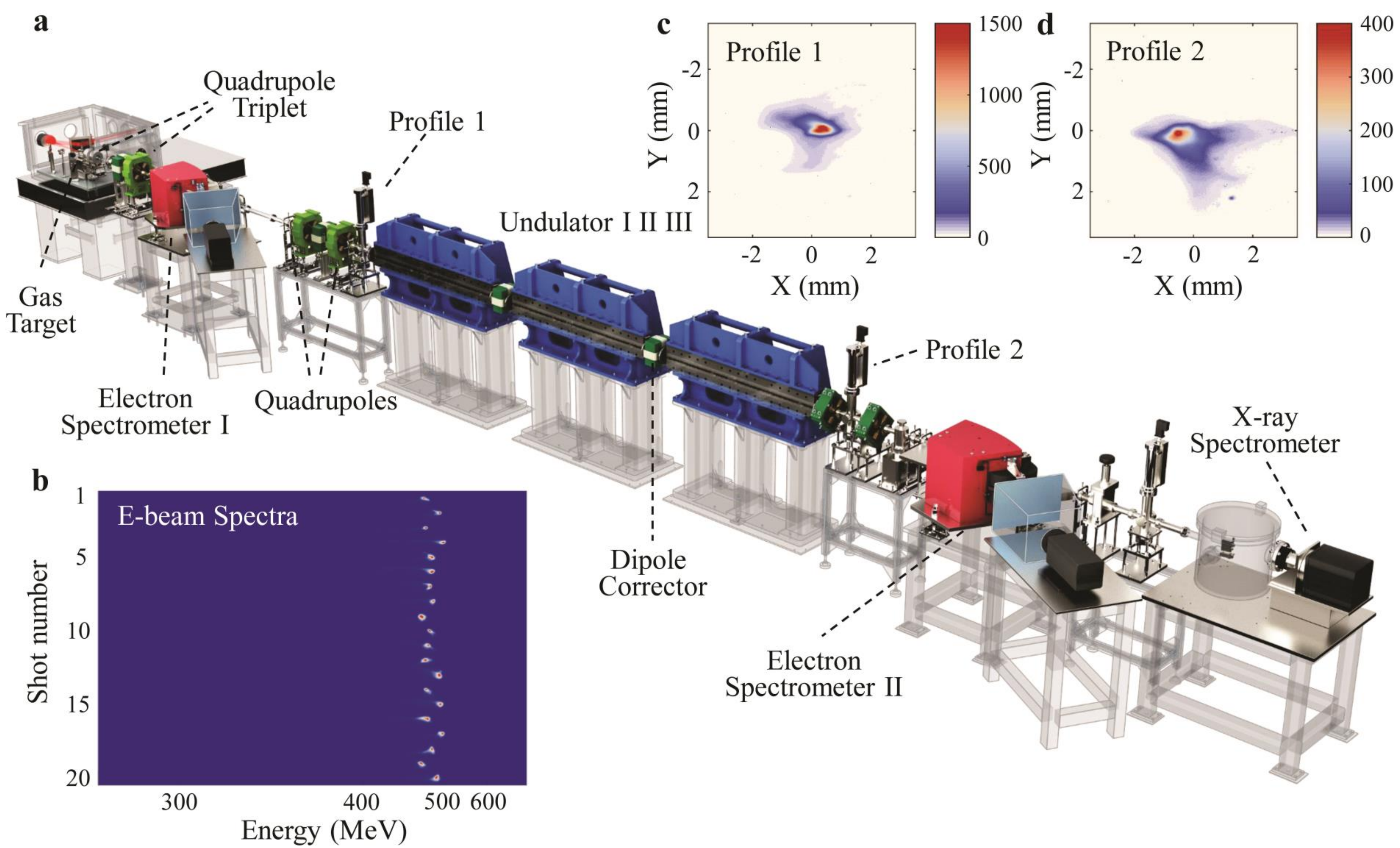
Table-top free electron laser

Table-top free electron laser: schematic layout

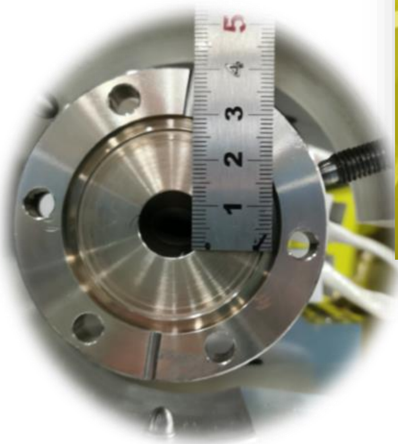


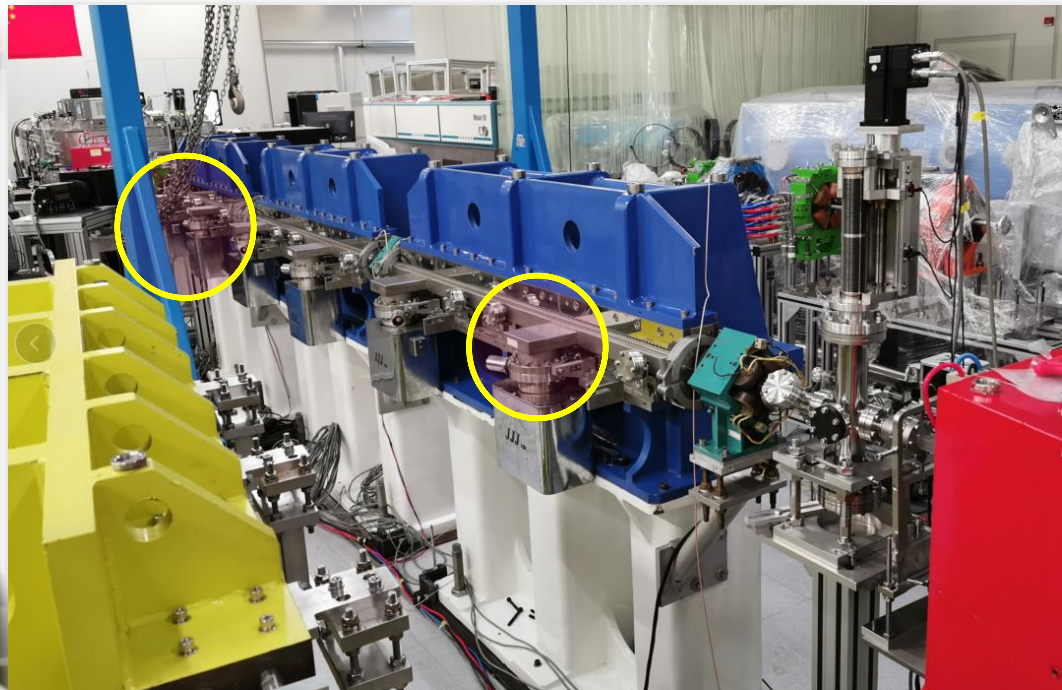
Device schematic of table-top free electron laser based on LWFA.

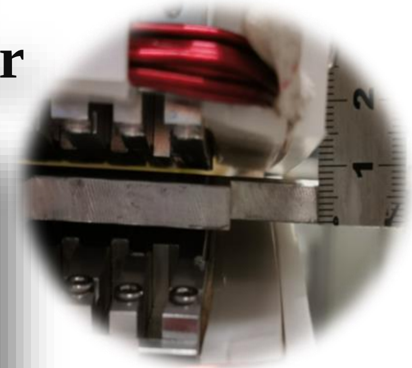
Table-top free electron laser

The facility has a total length of 12 m from the gas target to the x ray spectrometer

Pipe diameter < 15 mm







Inner diameter of undulator vacuum box ~4 mm

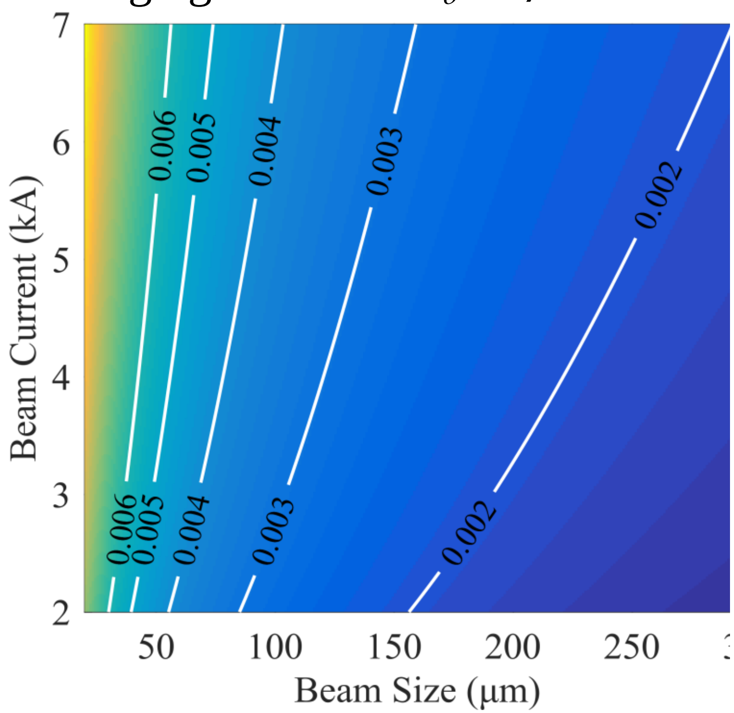
Higher stability and quality of the *e* beam from LWFA is required.

Table-top free electron laser: the beamline

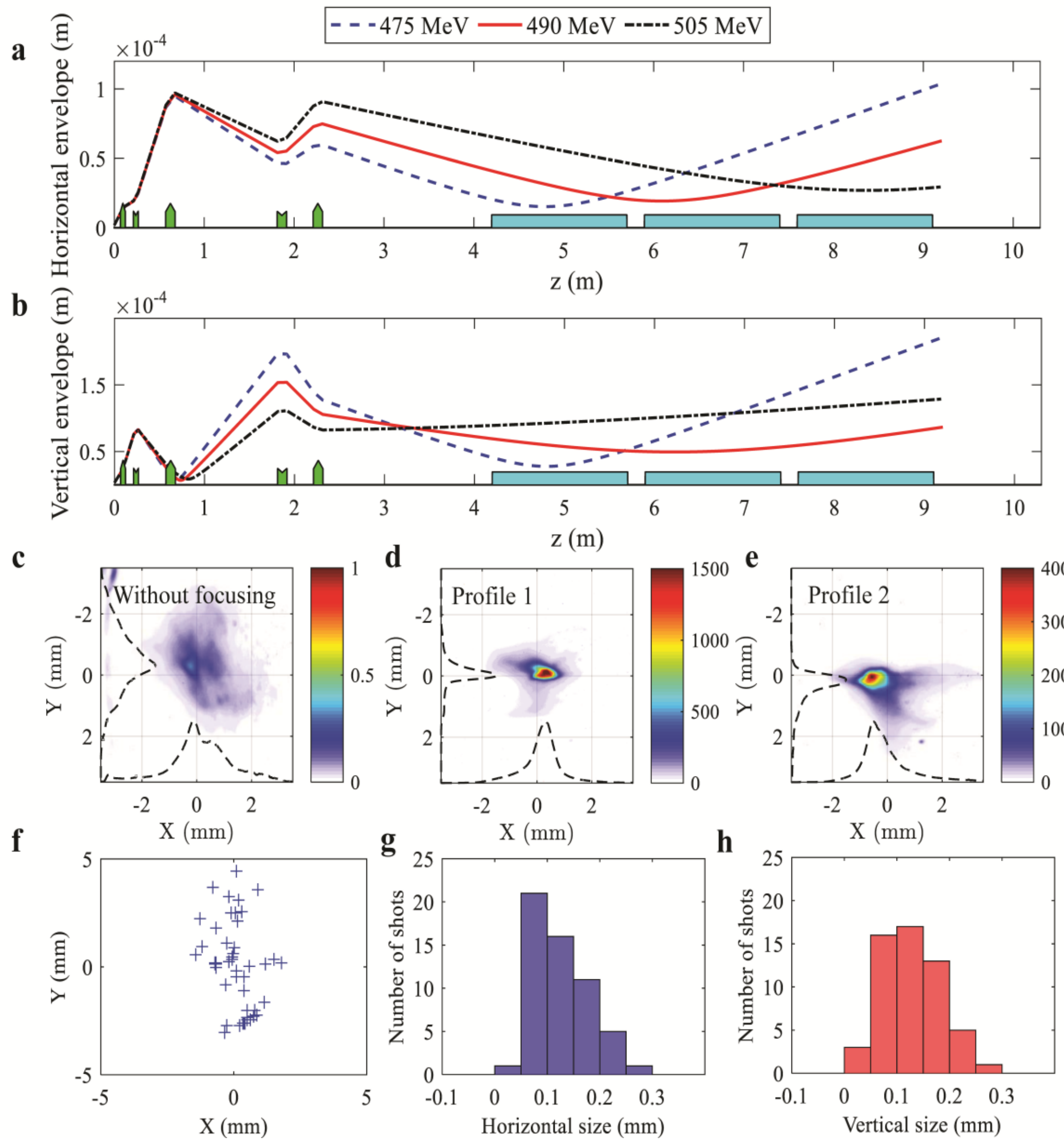
Pierce parameter:

$$\rho = \left[\frac{1}{16} \frac{I_p}{I_A} \frac{K_0^2 \left[JJ \right]^2}{\gamma_0^3 \sigma_\perp^2 k_u^2} \right]^{\frac{1}{3}}$$

For high gain FEL: $\sigma_\delta \ll \rho$

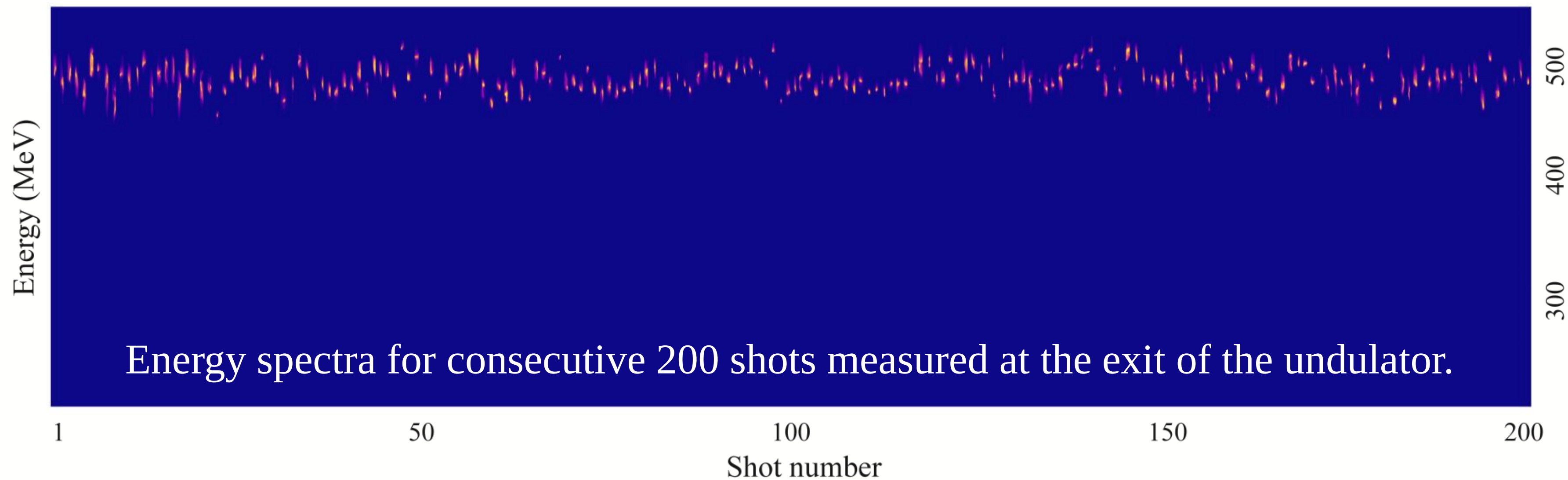


- RES~ 0.2-1.2%
- Charge ~ 10-50 pC
- Divergence~ 0.1-0.4 mrad



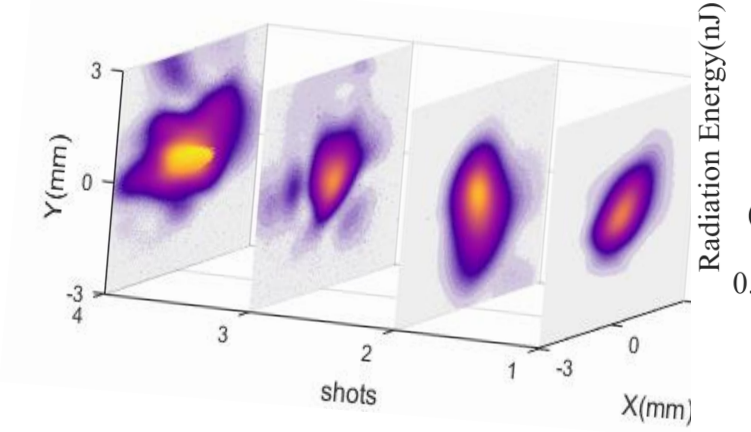
The minimum *e* beam size can be focused to 20~30μm !

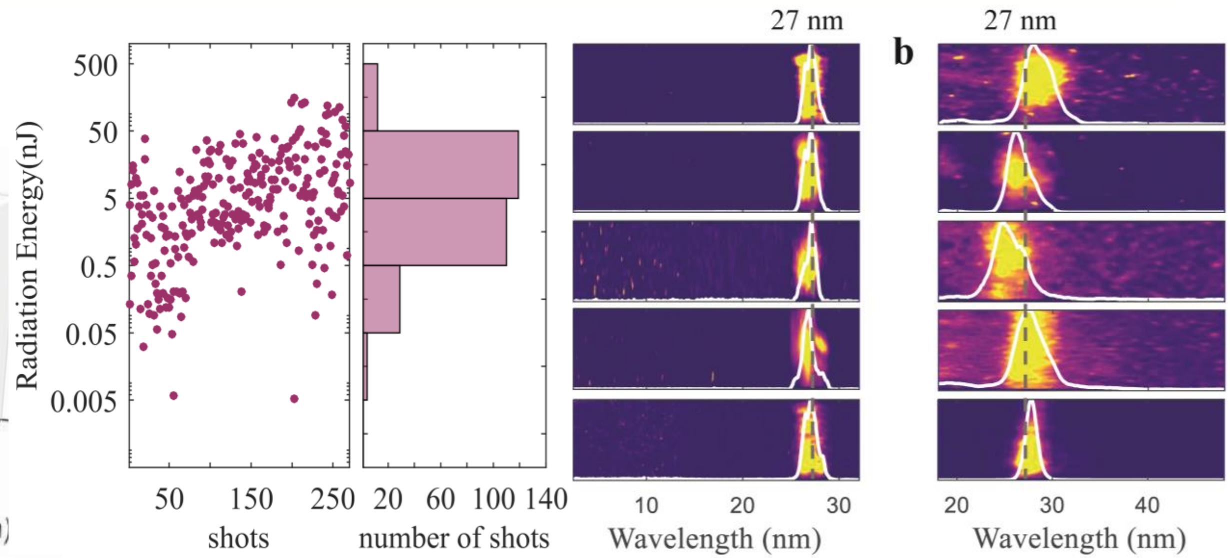
Table-top free electron laser: diagnosis



Energy spectra for consecutive 200 shots measured at the exit of the undulator.

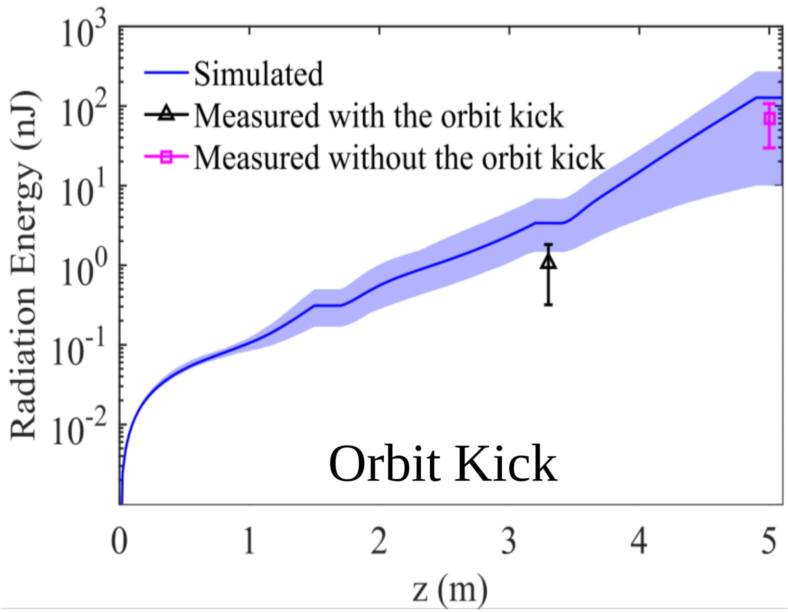
The radiation signal measured at 12 m from the gas target.

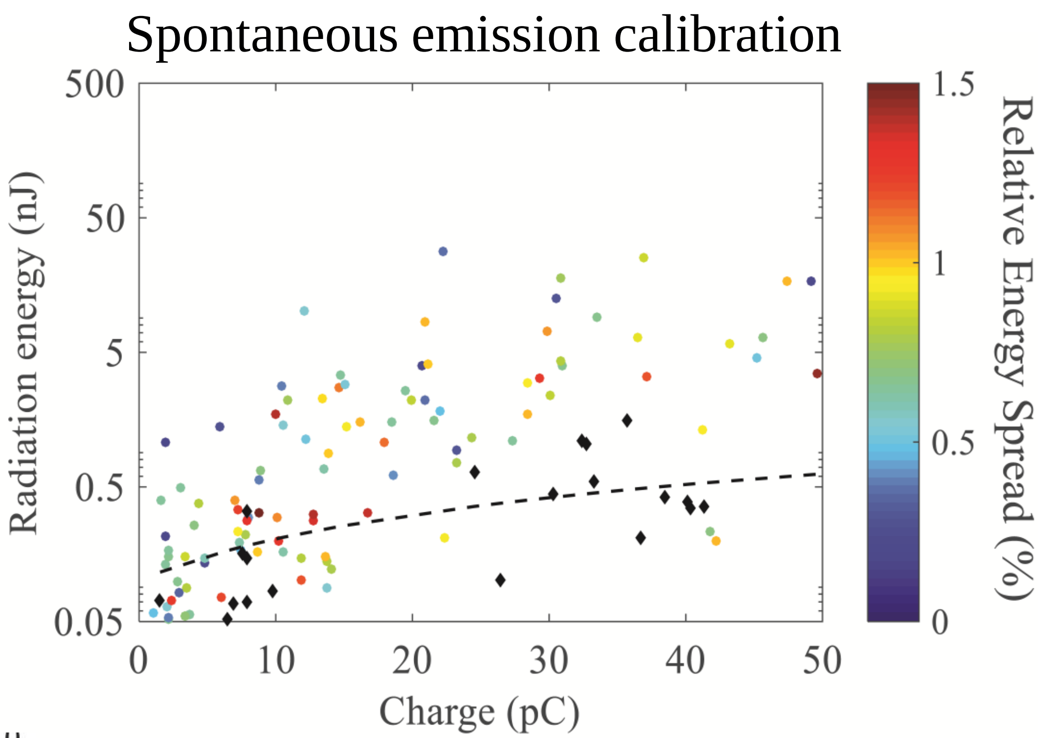


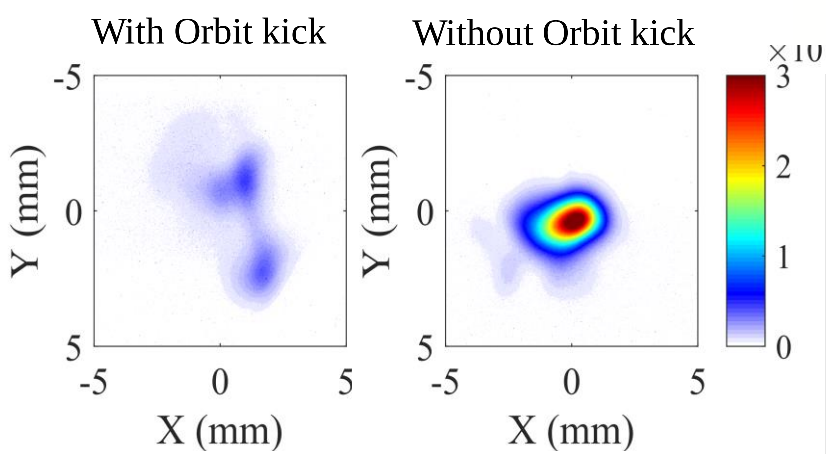


- ➢ The maximum radiation energy reaches ~100 nJ; The fluctuation of the radiation energy comes from the jitter and the shot noise of the *e* beam.

Table-top free electron laser: exponential gain



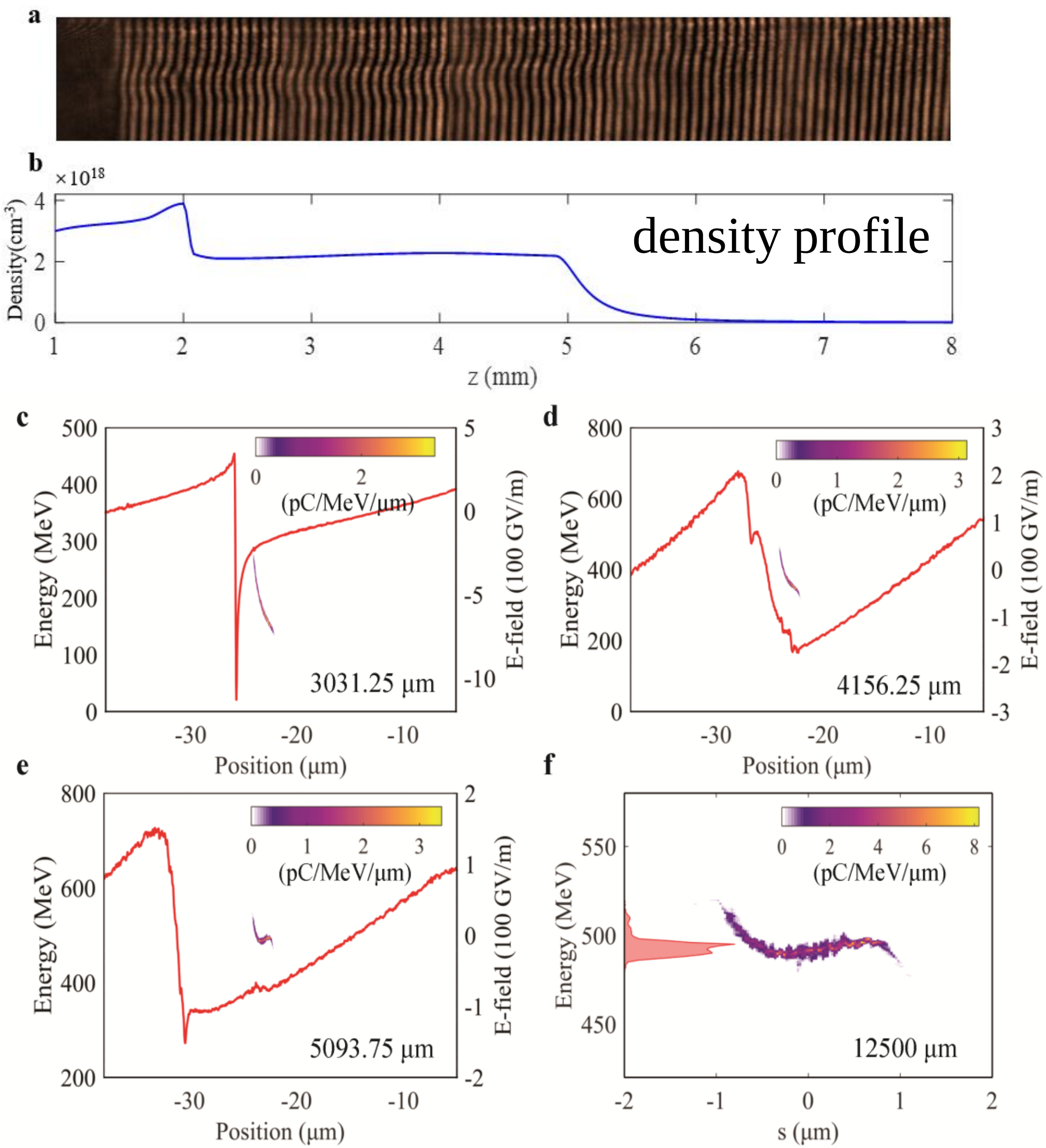




Demonstration of exponential gain:

- **Orbit kick method:** The gain process was spoiled by kicking the *e* beam at the entrance of the third undulator; The maximum power gain in the third undulator approximates 100-fold.
- **Spontaneous emission calibration:** The spontaneous emission curve was fitted by spoiling the energy spread of the *e* beam.

Table-top free electron laser: start-to-end simulation



- Injection controlling：
  - Pulse duration；
  - Current profile;
  - Transverse emittance;
- Chirp compensation:
  - Laser evolution + beamloading；
- Phase space matching (plasma to vacuum)
  - Emittance evolution;
  - Twiss parameters (α, β);

E-beam parameters in simulation:

Energy: 495 MeV;

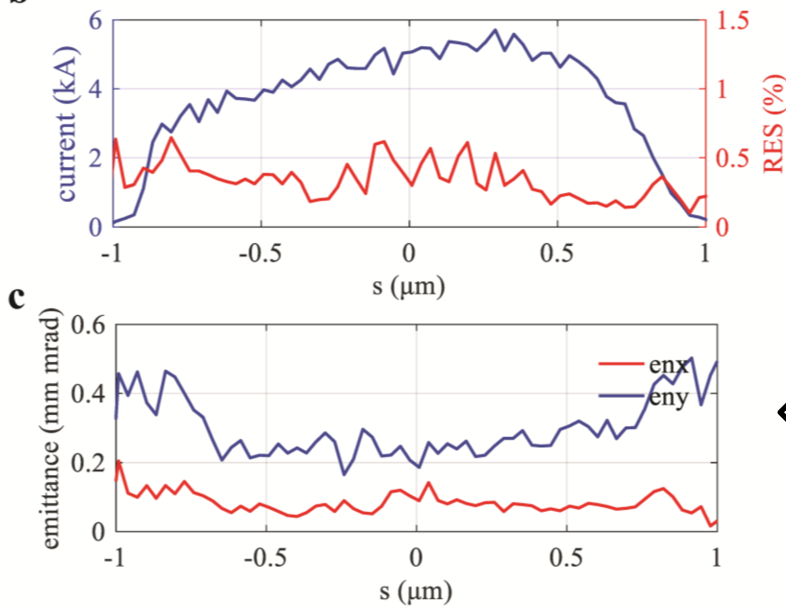
Global energy spread (93%): 0.67%;

Emittance: 0.23 / 0.73 μm rad;

Charge: 25.4 pC.

Table-top free electron laser: start-to-end simulation

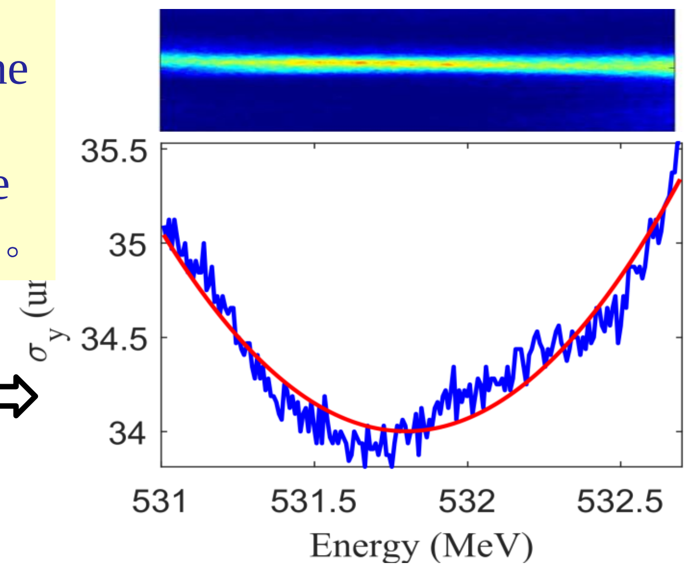
Slice parameters of the *e* beam



The transverse emittance of the e beam was measured to be 0.25 mm mrad。

Consistent with each other

Diagnostic on *e*-beam emittance:



Combining the experiments and simulation:

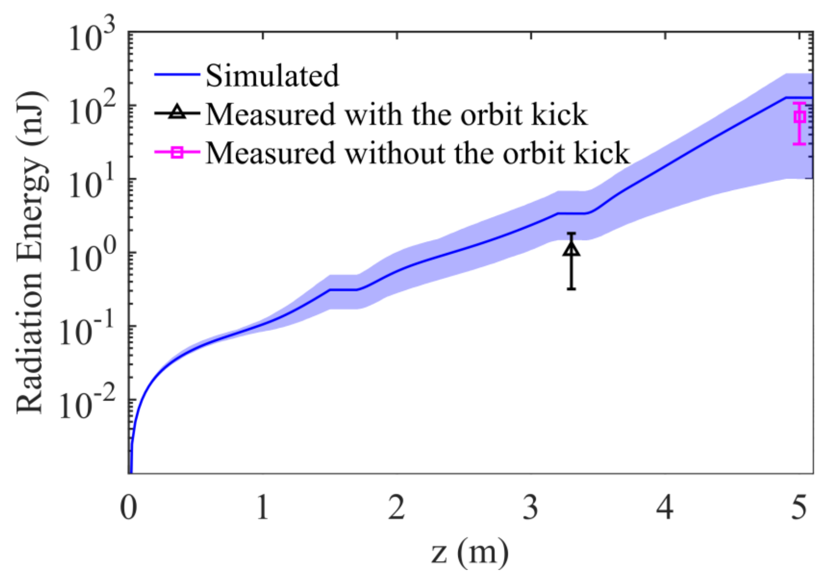
$$\eta_d = 0.1301 \quad \text{(diffraction parameter)}$$

$$\eta_\varepsilon = 0.0138 \quad \text{(angular spread parameter)}$$

$$\eta_\gamma = 0.3623 \quad \text{(energy spread parameter)}$$

Xie's scaling law：

$$L_G = L_{G0}(1+\Lambda) = 0.4\text{m} \quad \text{(power gain length)}$$



Comments from international peers

- “the authors are the first to realize this major milestone.” And ever since then, the LWFA-driven FEL was considered the most essential milestone to be reached…”; (James Rosenzweig ， UCLA）

- “…this represents an important step forward in the development of compact FEL-s based on plasma-based acceleration sources…” , “I wish to congratulate the authors for this outstanding achievement…”

  (Luca Giannessi, FERMI)

NEWS AND VIEWS | 21 July 2021

A step closer to compact X-ray lasers

Light sources known as free-electron lasers can produce intense X-ray radiation for a wide range of applications. The process usually needs huge particle accelerators, but an experiment shows how to overcome this limitation.

Luca Giannessi

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

Outlines

1. Background and motivations
2. Major progress in developing high-quality laser wakefield accelerators (LWFAs) at SIOM
3. Table-top free electron lasing based on a laser wakefield accelerator
4. Summary

Summary

High-quality laser wakefield accelerators (LWFAs) at SIOM:

- high-brightness high-energy e-beam generation;
  - Self-injection and energy chirp controlling.
- Laser system optimization and stable high-quality LWFA;
  - The reproducibility increases from 30% to 100%
- Near-GeV, 2‰-level e beam generation;
  - synergic injection + chirp compensation;

Table-top free electron lasing based on a laser wakefield accelerator:

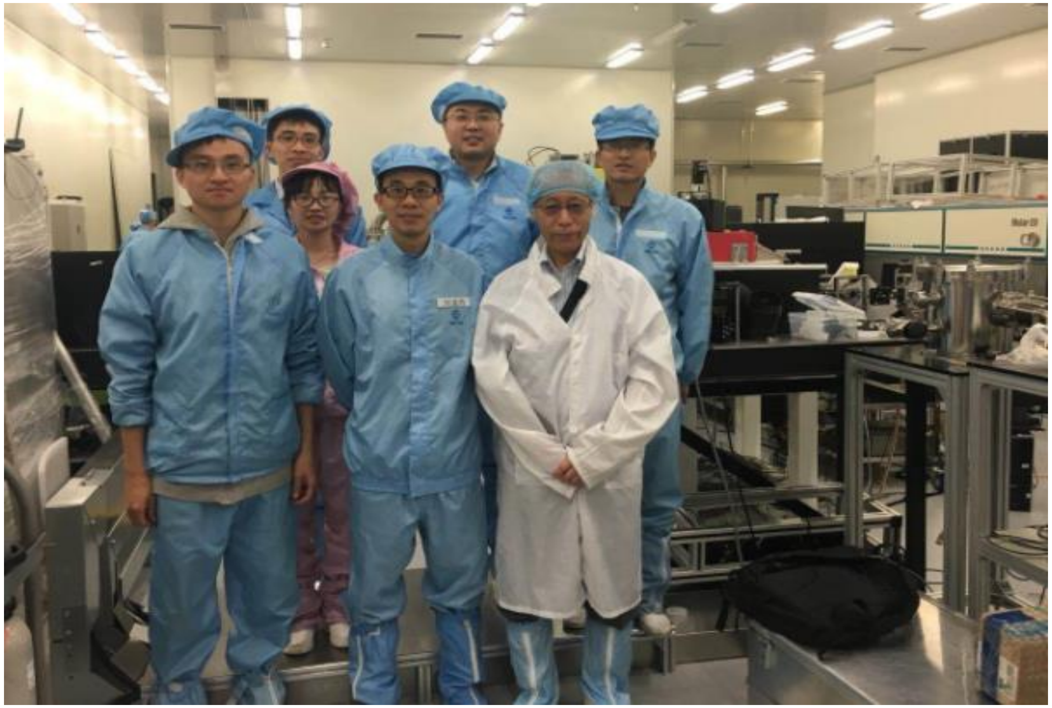
- Diagnosis of electron beam and radiation signals;
- Demonstration on exponential gain;
  - Orbit Kick method;
  - Spontaneous emission calibration.
- The start-to-end simulation and analysis on the lasing process.

Acknowledgement

In 2004， Kazuhisa Nakajima of Japan visited SIOM

In 2008， Led by Prof. Kazuhisa Nakajima of Japan, SIOM started experimental research on LWFA using ablative capillary.

………



We are particularly grateful to Professor Nakajima. He has been promoting experimental research on LWFA in China and has carried out many cooperation with many universities and research institutes, including SIOM.

Thank you for your attention!

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