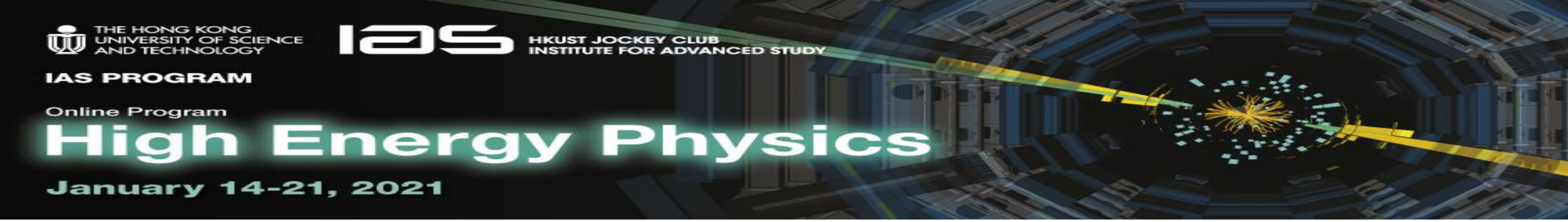


Laser Plasma Acceleration and Its Applications

Jiansheng Liu

Shanghai Normal University

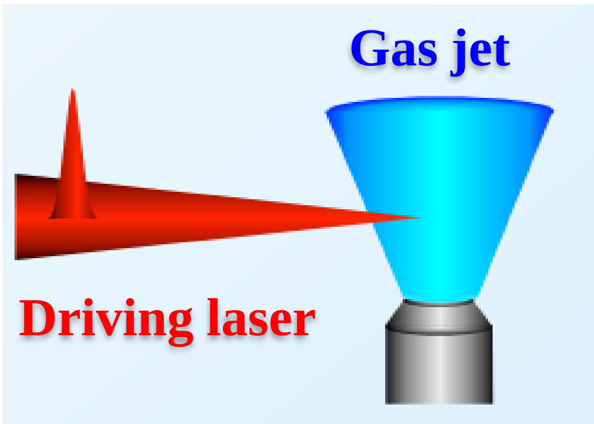
Shanghai Institute of Optics and Fine Mechanics (SIOM), CAS

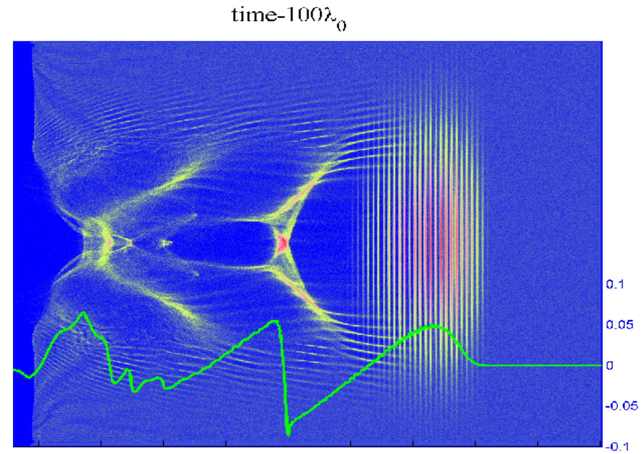
Outline

1. Background and motivations
2. High-quality e-beam generation from a sophisticated laser wakefield accelerator (LWFA)
3. Generation of x- and γ-ray sources based on a LWFA
4. Summary

Motivations: LWFAs are compact accelerators

- **Laser wakefield accelerators—Compact particle accelerators**

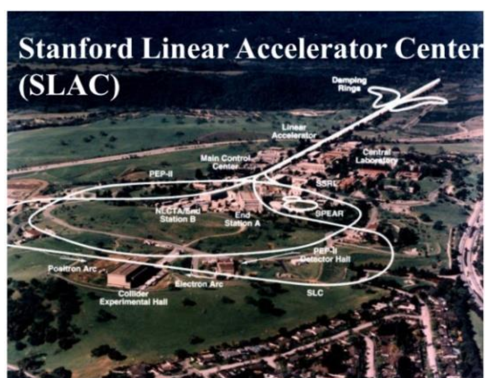




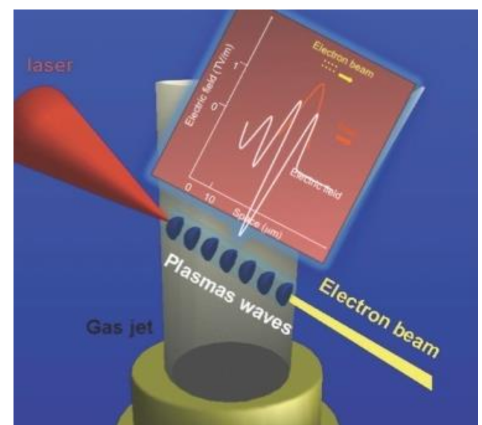
LWFA: Accelerating gradient ~100 GV/m

Stanford LINAC, 2 miles long

RF cavity (1 m-long)
(gradient= $10^{7\text{-}8}$ V/m)



RF accelerator

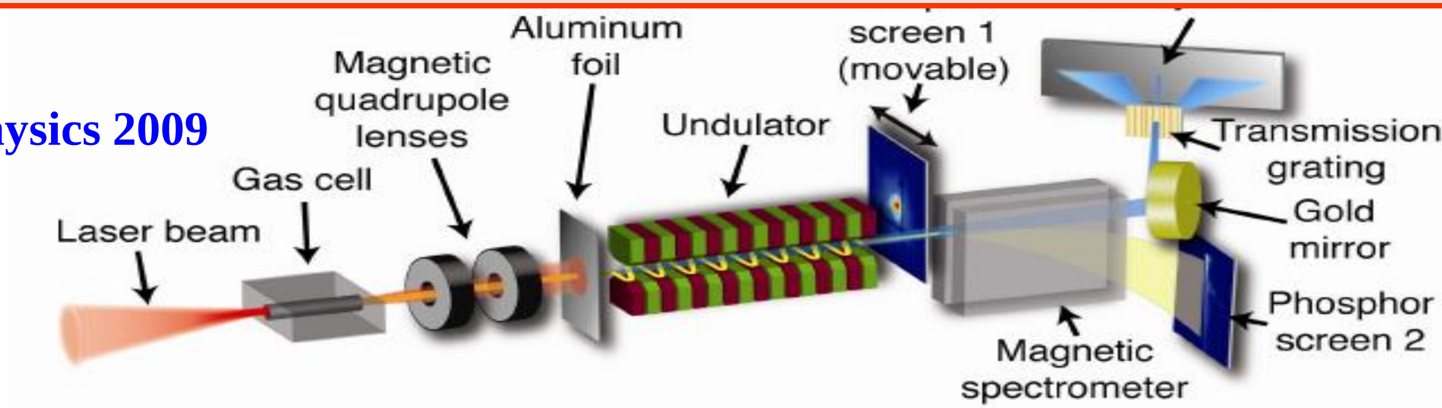


Laser Pulse Phenomena and Applications

Compact light sources based on a LWFA

However, high-brightness light sources rely on the generation of stable and high-brightness electron beams from a LWFA

Nature Physics 2009

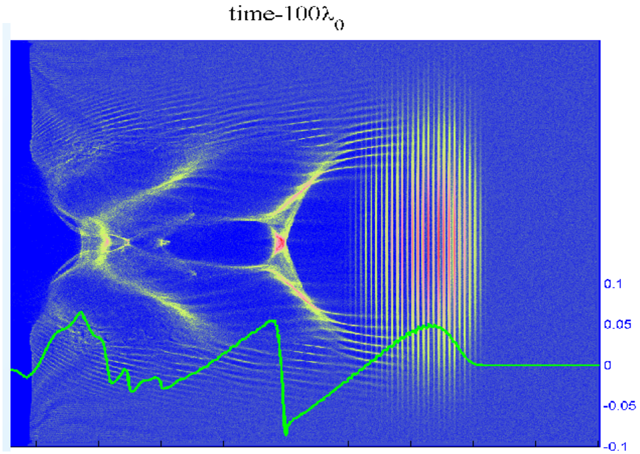


Outline

1. Background and motivations
2. High-quality e-beam generation from a sophisticated laser wakefield accelerator (LWFA)
3. Generation of x- and γ-ray source based on a LWFA
4. Summary

Generation of controllable high-quality high-energy e-beam: decoupling electron injection and acceleration, and energy control

Single-Stage LWFAs



Single-stage LWFAs

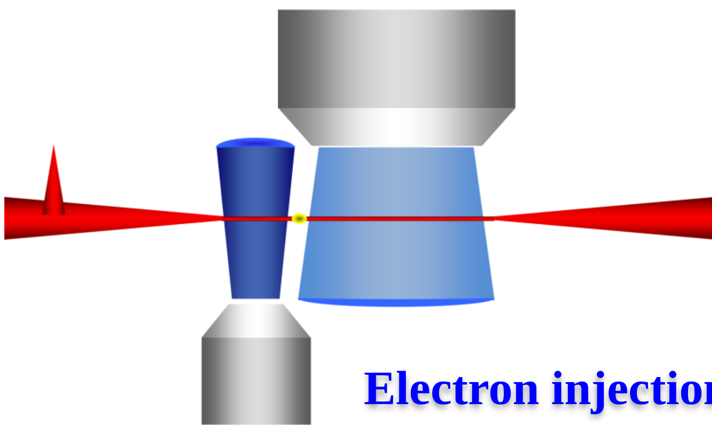
Electron injection — Electron acceleration

High density
Strong nonlinear

Low density
Quasi linear

contradiction

Cascaded/Staged LWFAs



Electron injection and acceleration are decoupled

Cascaded LWFAs

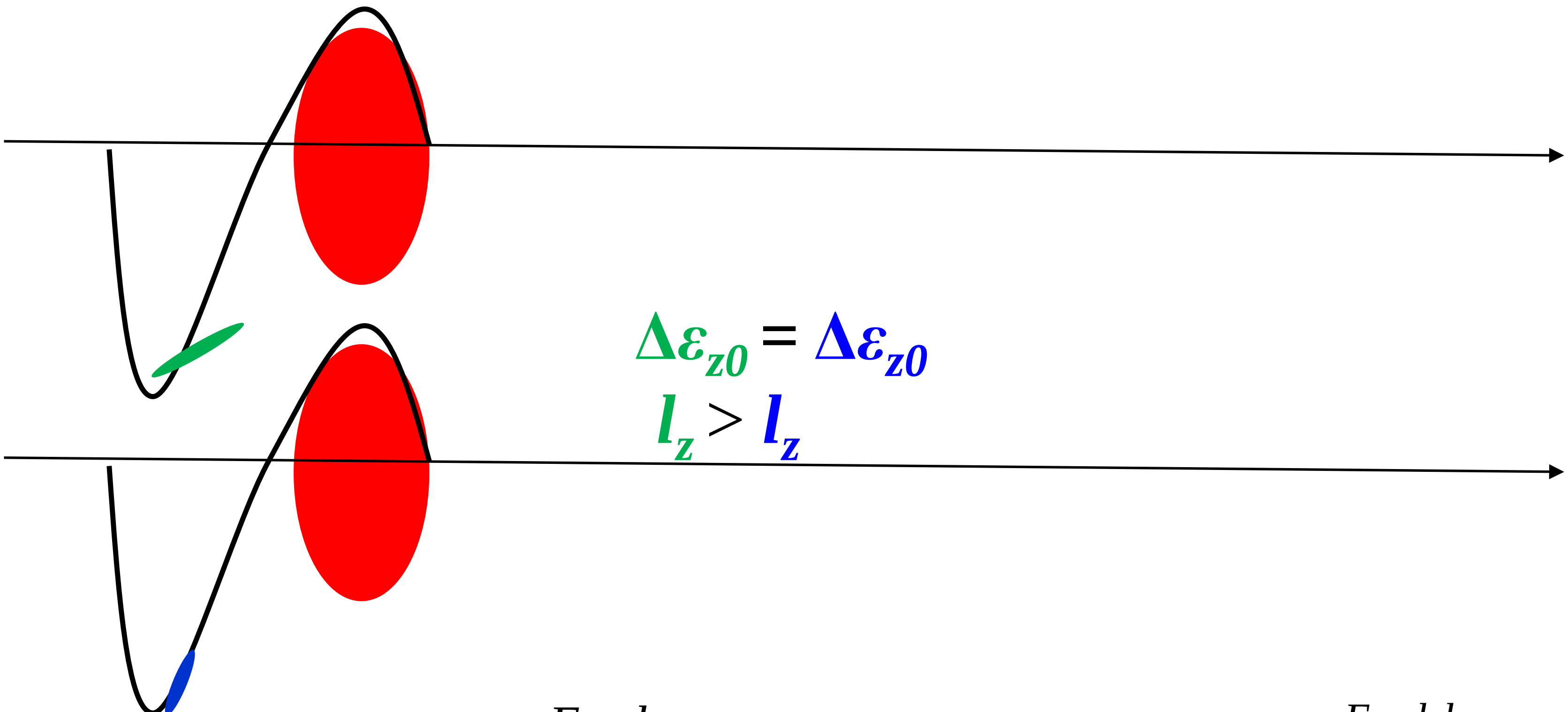
3 major issues

- Electron injector
- Energy chirp control
- Efficient acceleration

Controllable high-quality high-energy e-beams

Minimization of energy spread in a cascaded LWFA via velocity bunching (e-beam compression)

➢ Evolution of energy spread and energy chirp in a LWFA



$$\Delta E = E_{back} - E_{front} = -E' l_z \approx \frac{E_{\max} l_z}{R},$$

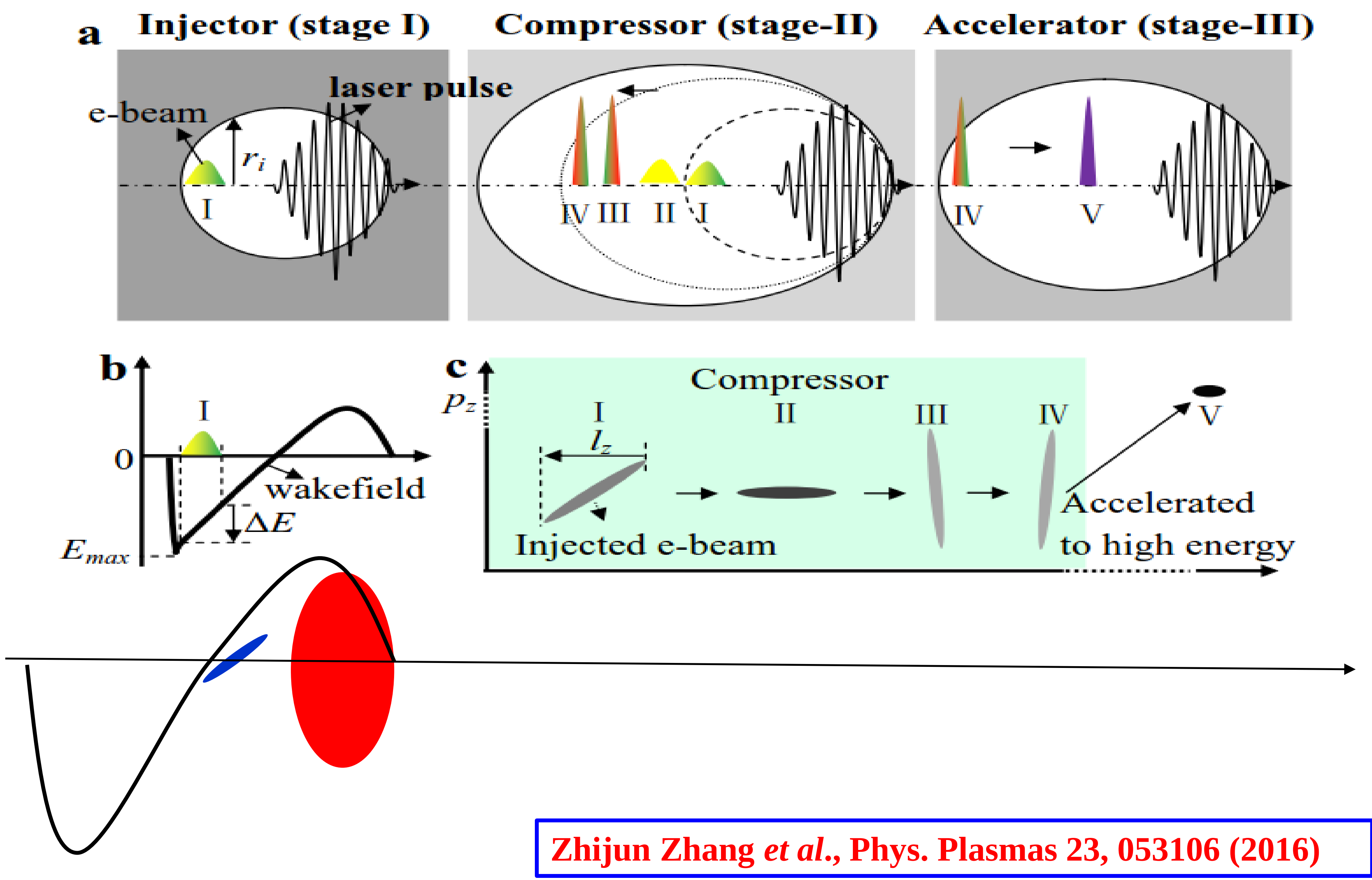
$$\Delta\varepsilon_z \approx \Delta\varepsilon_{z0} - e\Delta E l_a = \Delta\varepsilon_{z0} - \frac{eE_{\max} l_z l_a}{R},$$

$\Delta\varepsilon_z = \varepsilon_{back} - \varepsilon_{front}$

$$L_d = l_{am} \approx \frac{R}{eE_{\max}} \frac{\Delta\varepsilon_{z0}}{l_z} = \frac{R}{eE_{\max}} \Delta\varepsilon'_{z0}.$$

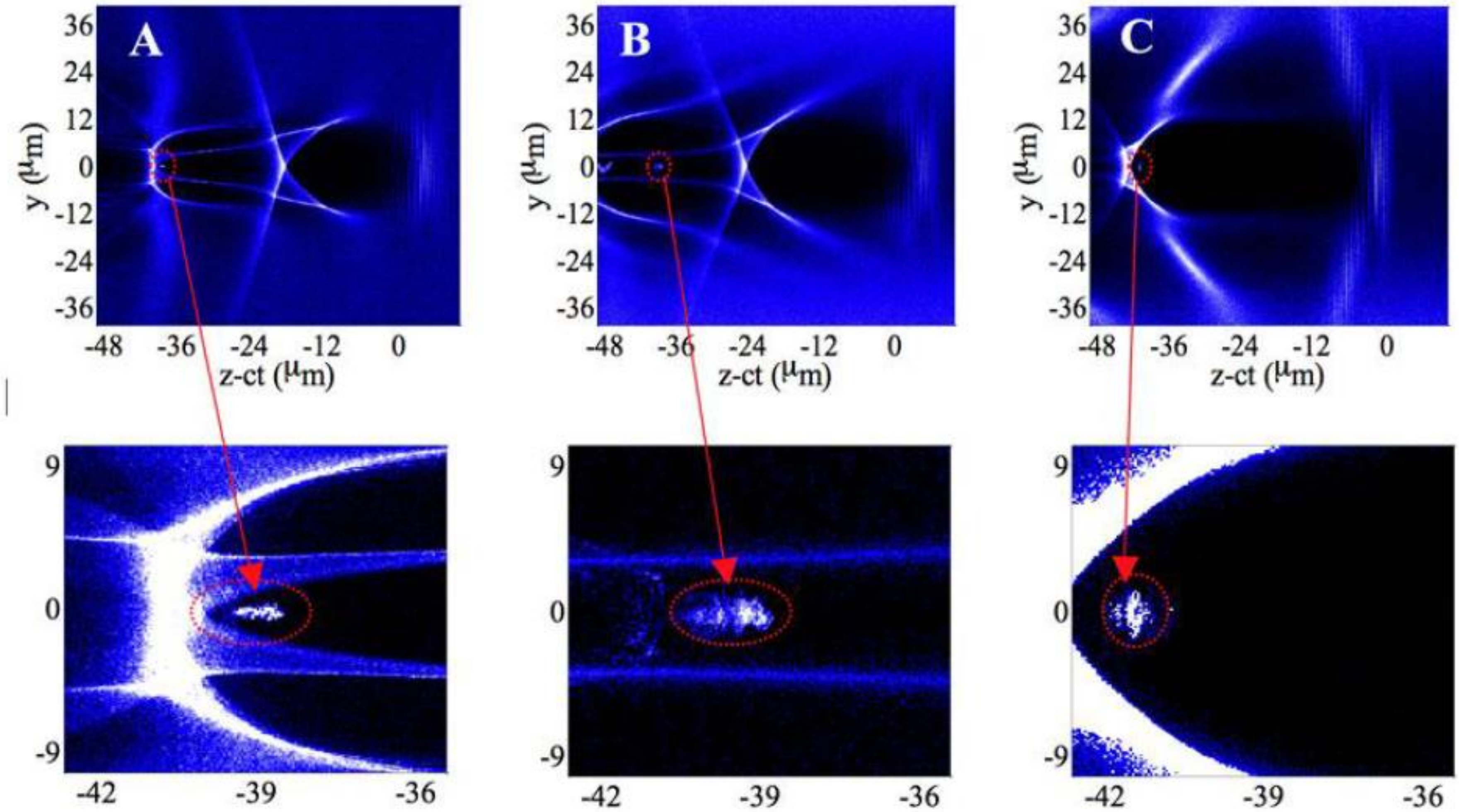
$$\left.\begin{matrix} l_z \downarrow \\ \Delta\varepsilon_{z0} \uparrow \end{matrix}\right\} \rightarrow \Delta\varepsilon'_{z0} \uparrow$$

Minimization of energy spread in a cascaded LWFA via velocity bunching (e-beam compression)



Zhijun Zhang *et al.*, Phys. Plasmas 23, 053106 (2016)

Minimization of energy spread in a cascaded LWFA via velocity bunching (e-beam compression)

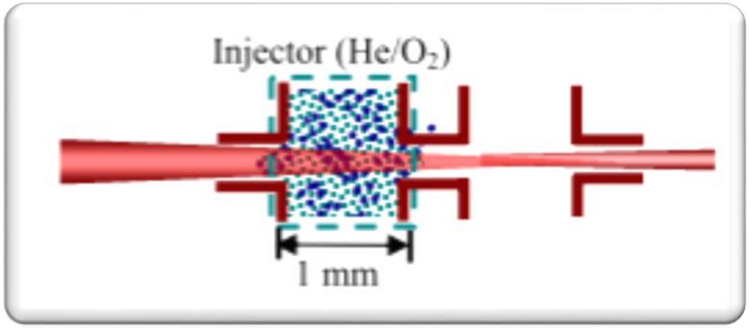


rms ES: 0.20%

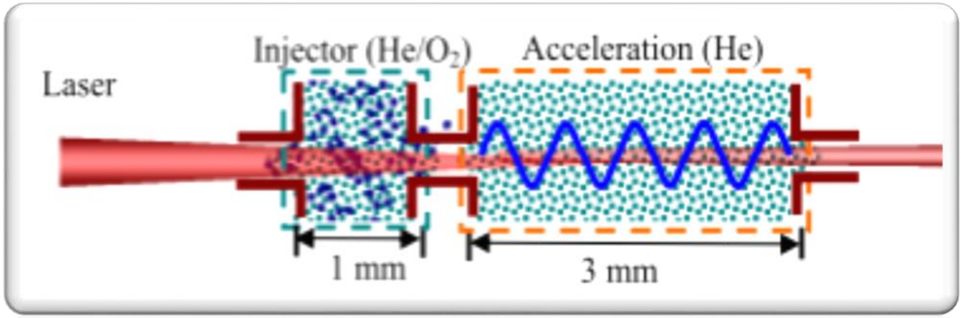
Zhijun Zhang *et al.*, Phys. Plasmas 23, 053106 (2016)

I. Design of a cascaded LWFA using ionization injection

Electron injector



Acceleration stage



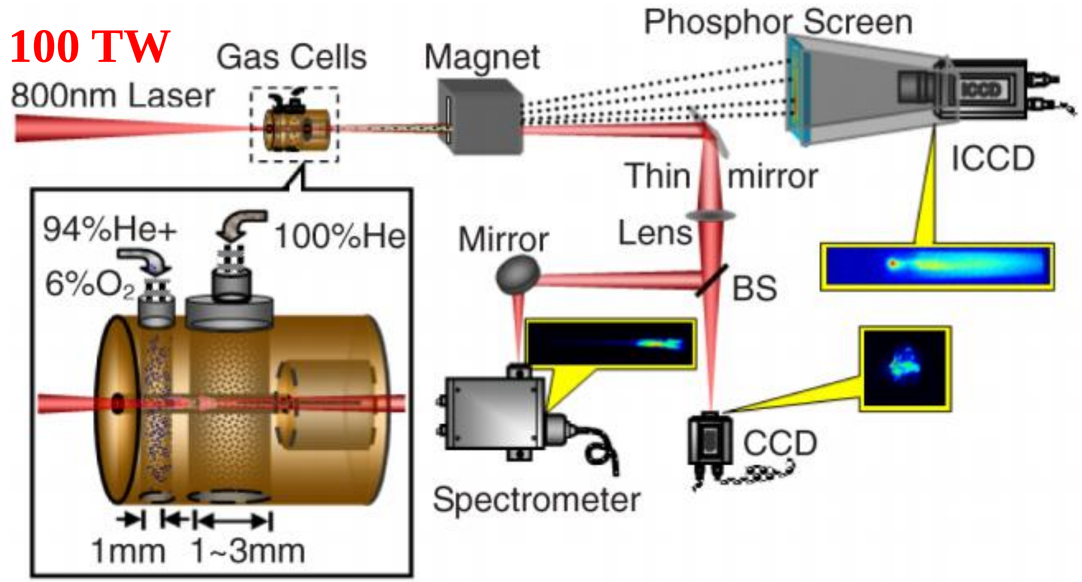
Advantages of using ionization-induced injection for the electron injector

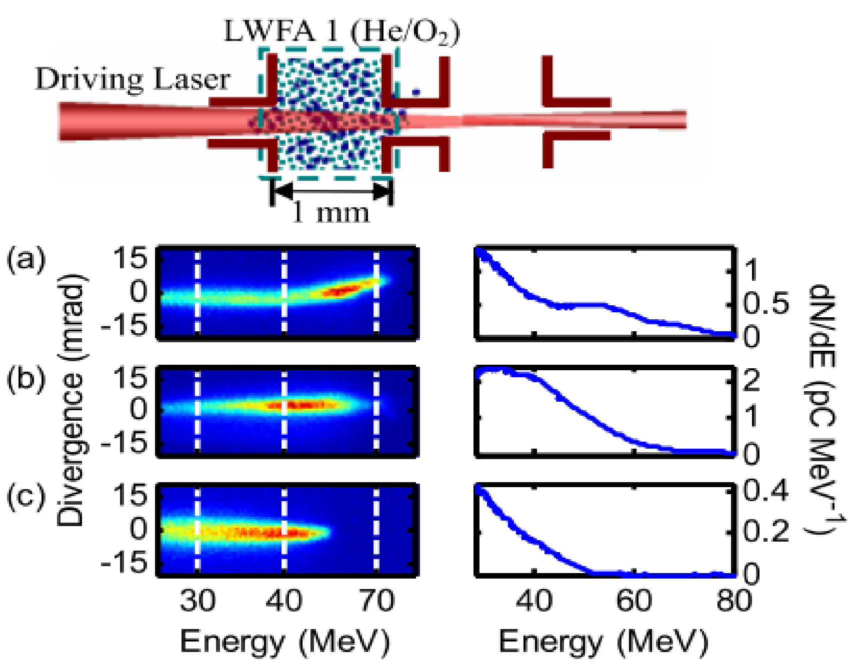
- Self-injection requires a high input power $P/P_c > 4$
- Ionization-induced injection works at lower laser power. $a_0 < 2$
- Ionization-induced injection can be operated at lower plasma density

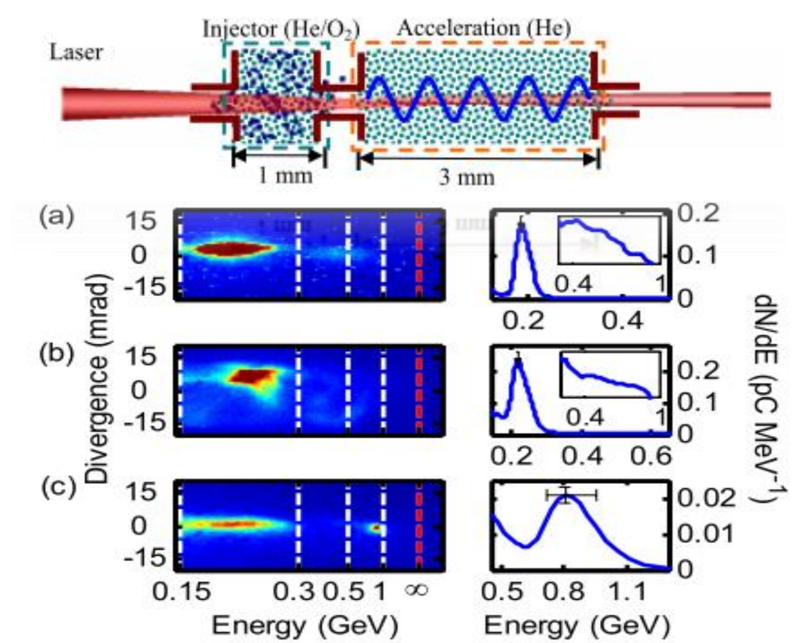
  nonlinear instability can be minimized

  phase matching for the electron seeding between the two-stage plasmas can be satisfied easily.

100 TW





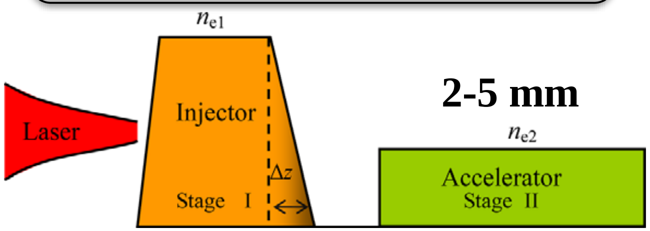


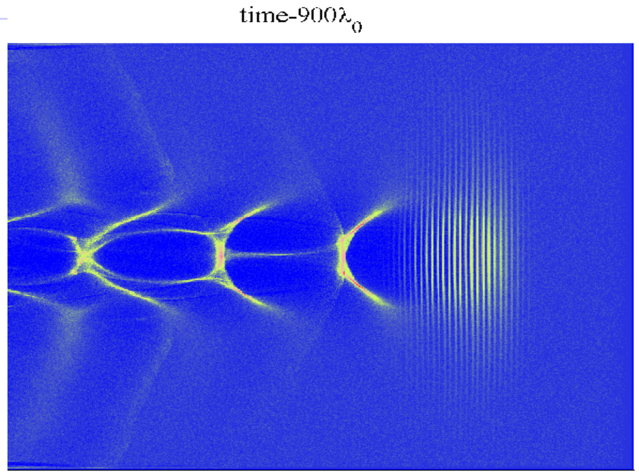
Jiansheng Liu *et al* PRL, 107, 035001 (2011)

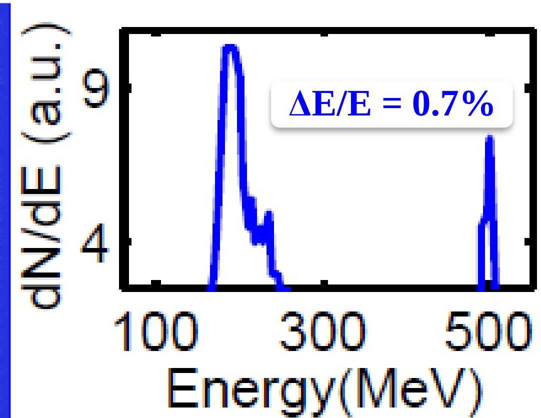
Demonstration of a cascaded LWFA using self injection

By optimizing the seeding phase of electrons into the second stage, electron beams beyond 0.5 GeV with a 3% rms energy spread were produced over 2 mm. Peak was further extended beyond 1 GeV by lengthening the second acceleration stage to 5 mm.[Appl. Phys. Lett.103, 243501(2013), Phys. Plasmas 19,023105(2012)]。

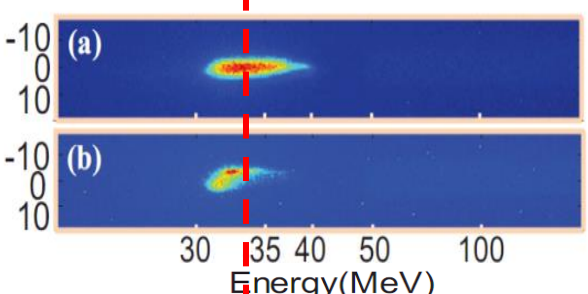
Cascaded LWFA (Gradient injection)

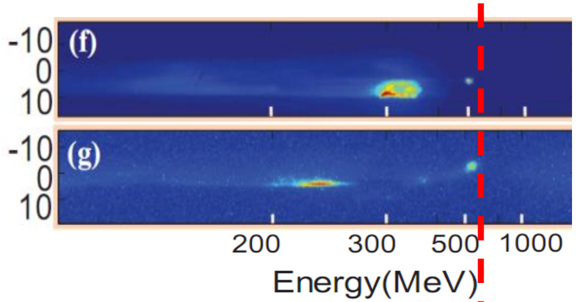


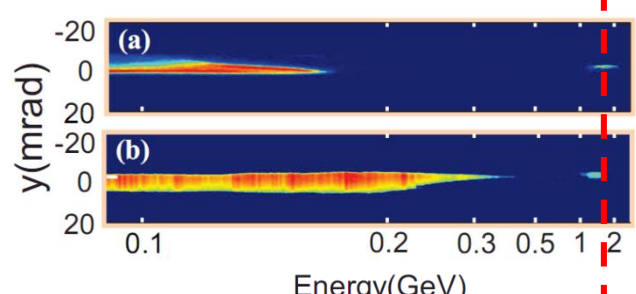




Experimental realization





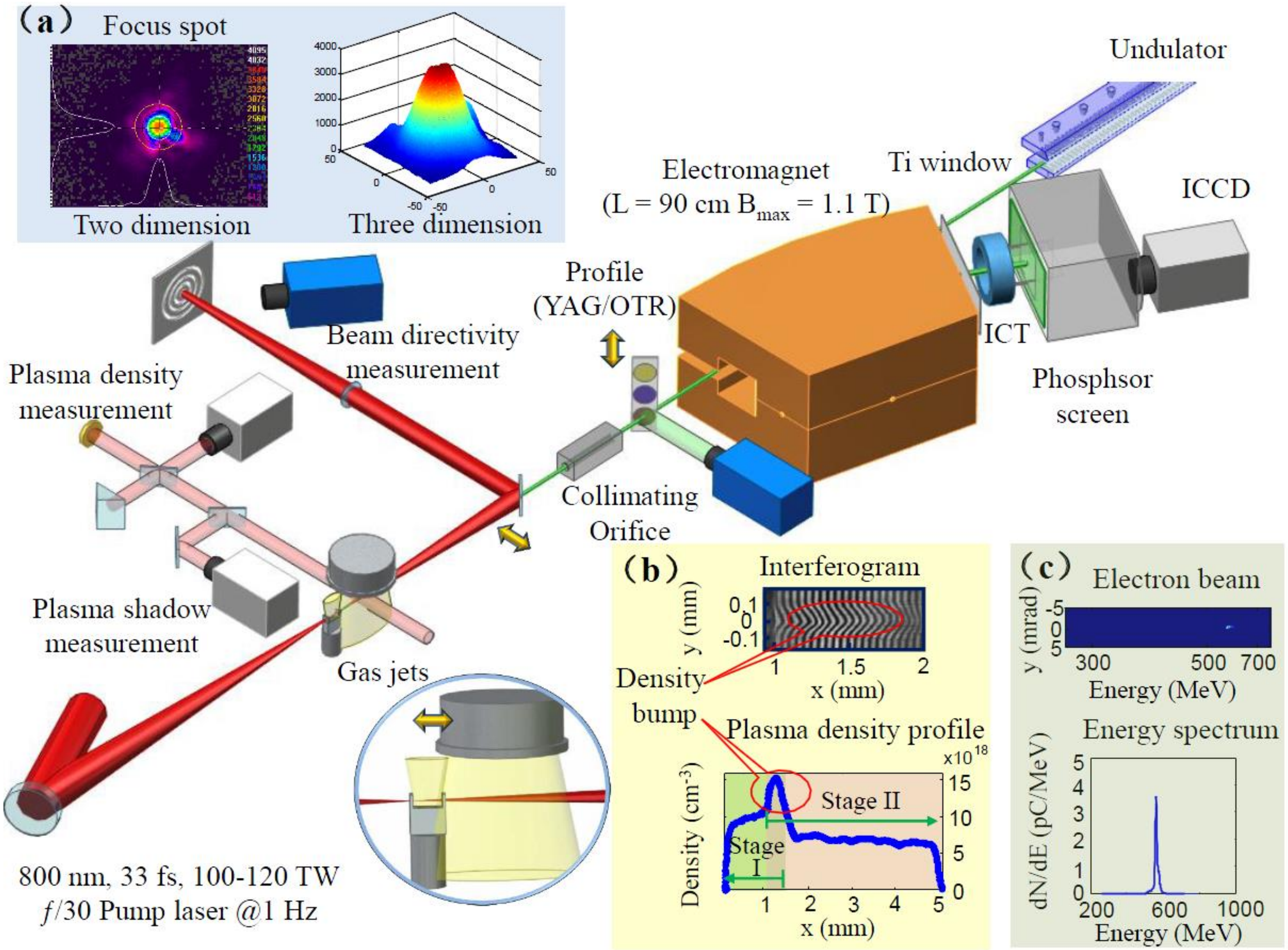


Electron injector
~32 MeV

Cascaded LWFA (1+2 mm)
530 MeV, ΔE/E ~ 3%

Cascaded LWFA (1+5 mm)
~1.3 GeV

High-Brightness High-Energy Electron Beams from a Laser Wakefield Accelerator via Energy Chirp Control



W. Wang et al., PRL 117,124801(2016)

High-quality high-energy electron beams from a cascaded LWFA

Energy chirp control

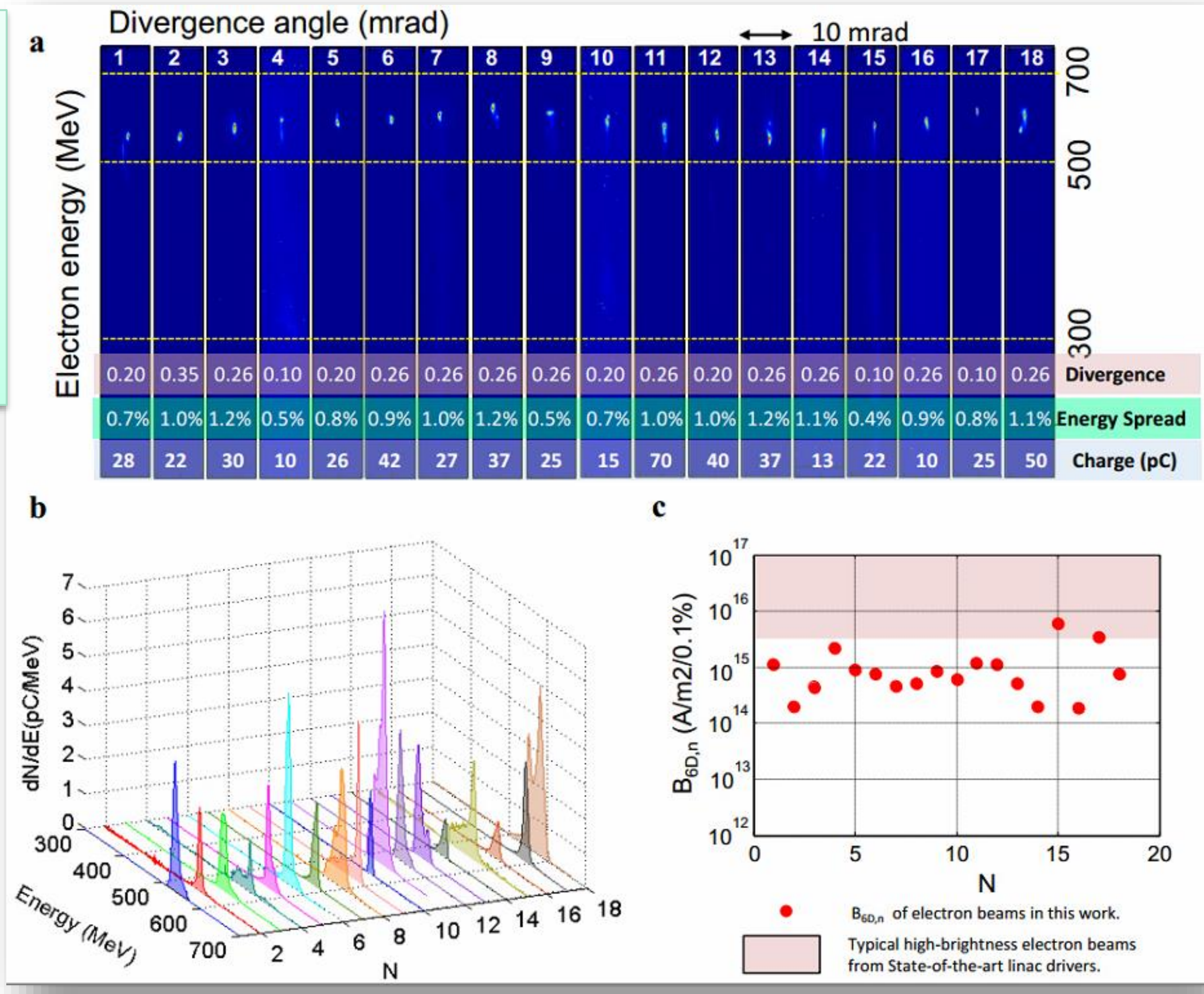
Peak energy: **0.4-0.8 GeV**
Energy spread: **<1%**
Beam charge : **up to 80 pC**
Divergence: **<0.3 mrad**
Stability: **>90%**
Energy fluctuation: **<5%**

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

$$I_p \approx 8kA$$

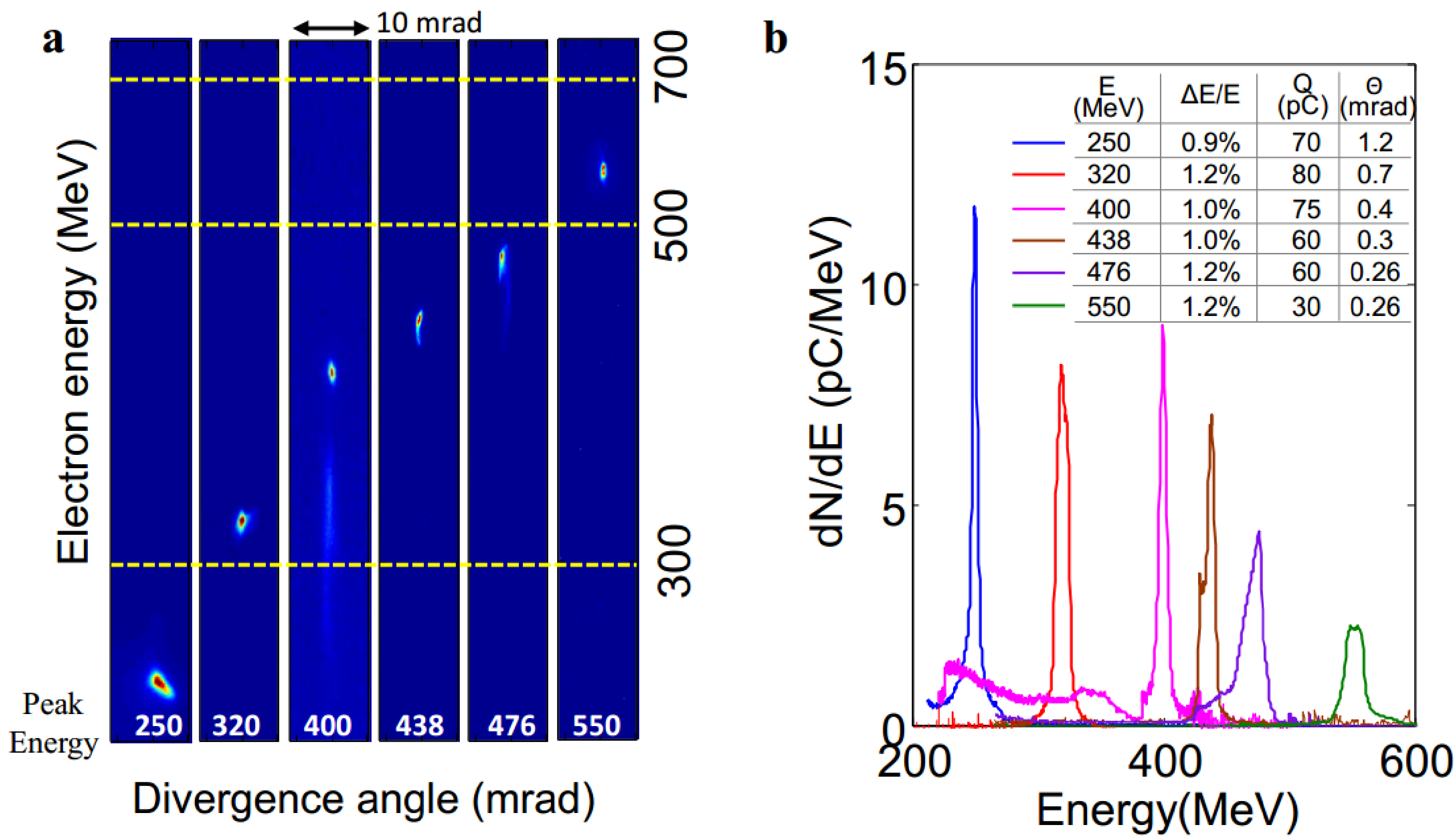
$$\varepsilon_n \approx 0.1\mu m$$

$$\sigma_\gamma < 1\%$$



Wentao Wang *et al*., Phys. Rev. Lett. 117, 124801(2016)

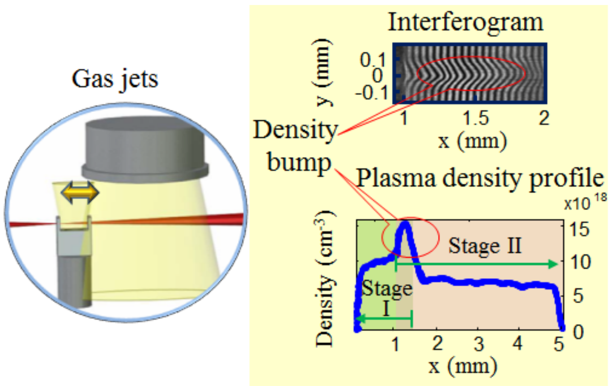
High-quality high-energy electron beams from a cascaded LWFA

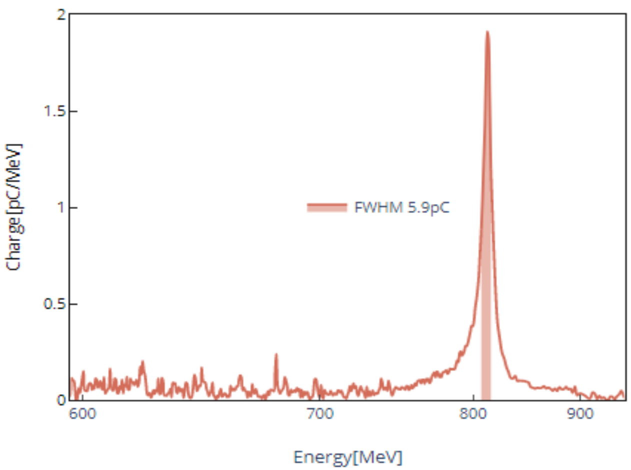


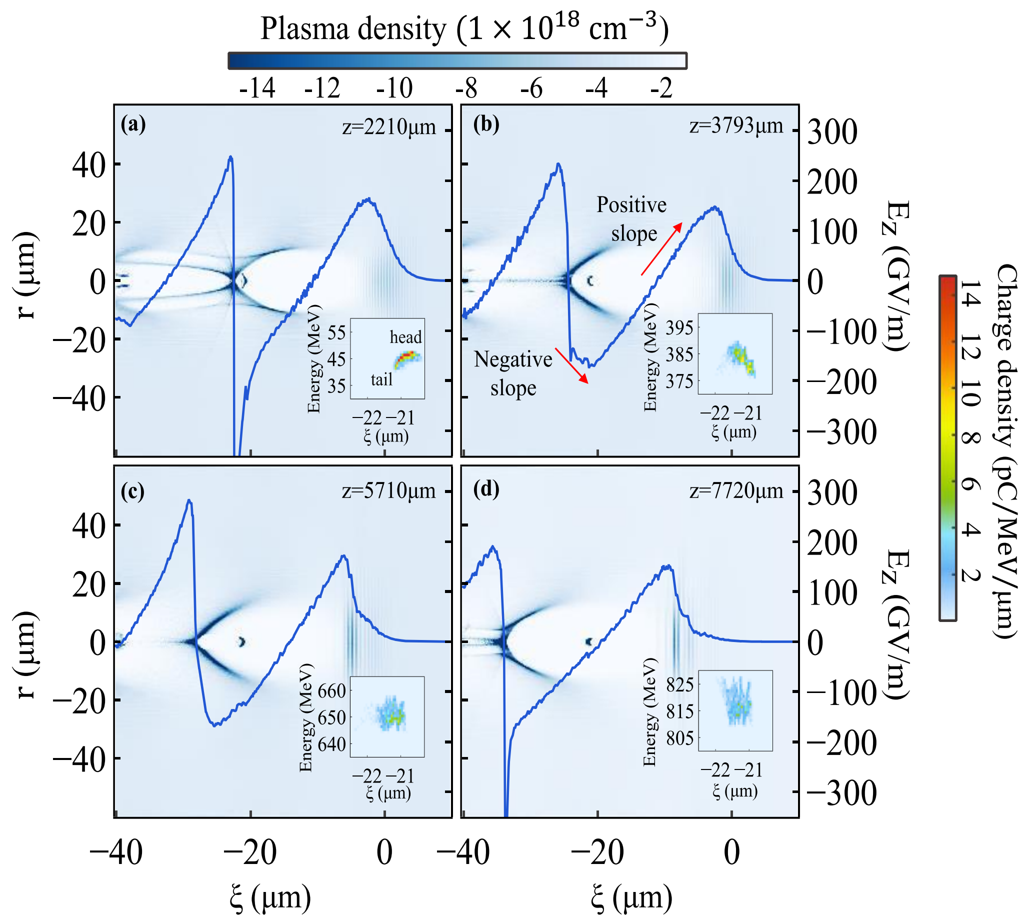
Wentao Wang *et al.*, Phys. Rev. Lett. 117, 124801(2016)

High-quality high-energy electron beams from a cascaded LWFA

➢ **Compression of energy spread via energy chirp control and beam loading**

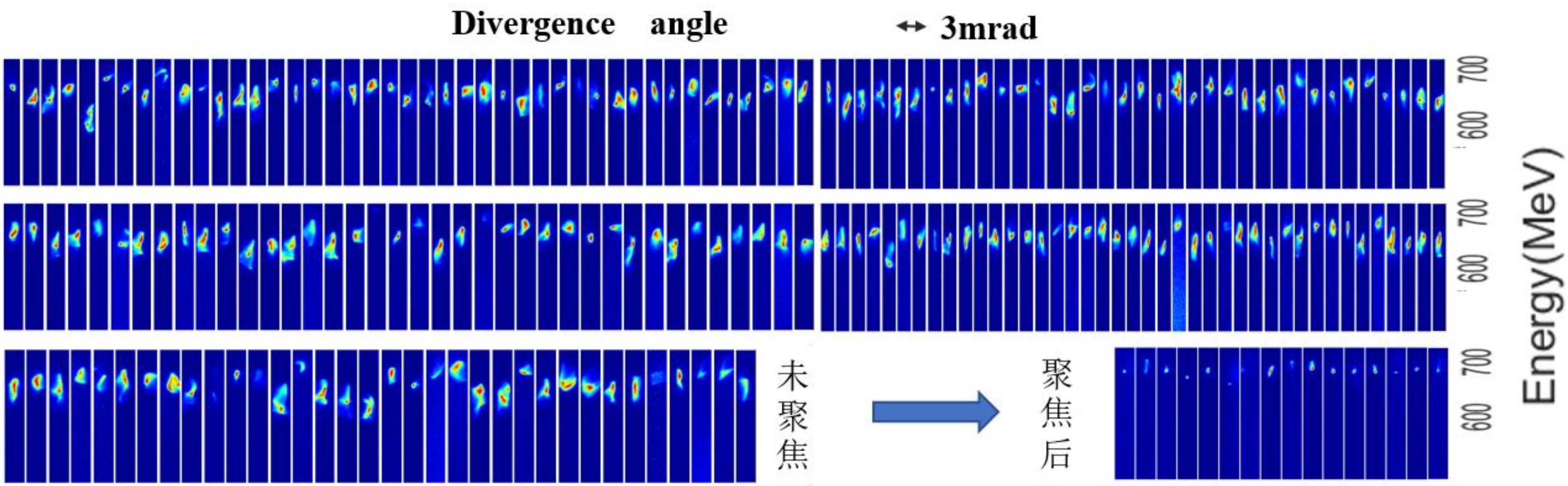




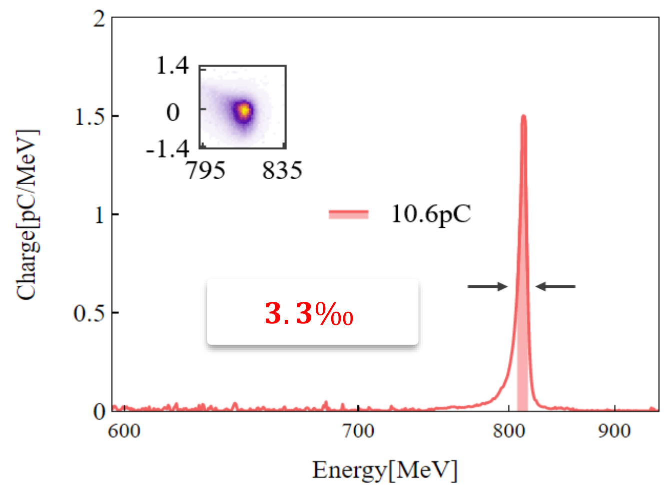


Wentao Wang *et al*., Phys. Rev. Lett. 117, 124801(2016)

Stable Near-GeV electron beams at a few-thousandth level



- ✓ ~ 100% Monoenergetic
- ✓ Energy spread 0.4-3%
- ✓ Energy fluctuation 4% (rms)
- ✓ Pointing stability 0.5mrad (rms)
- ✓ Beam charge 10-80 pC
- ✓ Consecutive shots

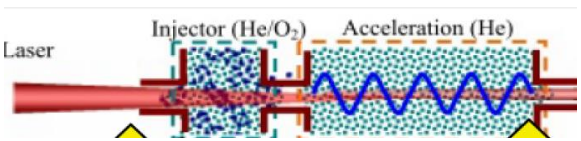


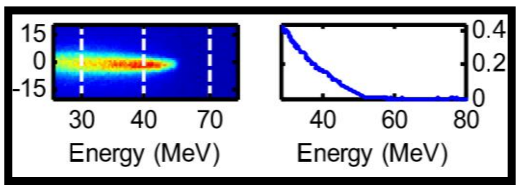
A big step from laser acceleration to accelerators！

Progress in generating high-quality electron beams via developing high-quality LWFAs

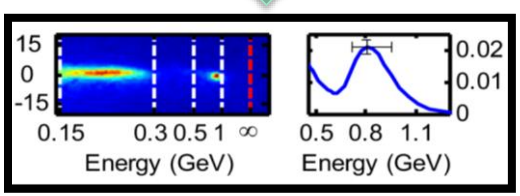
Ionization-induced injection

5.7×10^{19} cm^{-3} | **2.5×10^{18} cm^{-3}**





Injector: Energy spread 100%

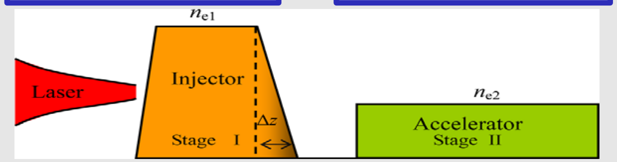


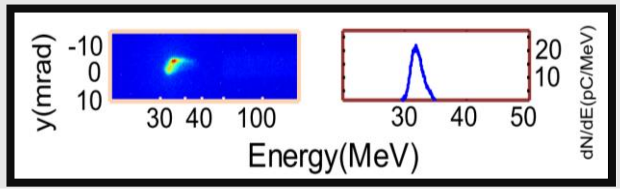
Injector+ Accelerator
Energy spread <25%

Phys. Rev. Lett. 107, 035001 (2011).

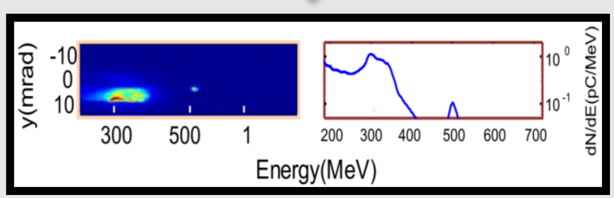
self injection

7-9$\times10^{18}$ cm^{-3} | **~3$\times10^{18}$ cm^{-3}**





Injector: Energy spread 10%

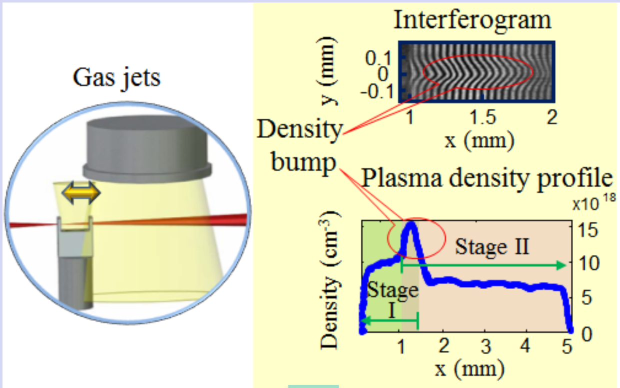


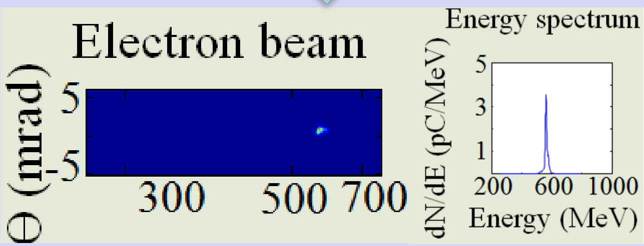
Injector+ Accelerator
Energy spread ~ 3%

Appl. Phys. Lett. 103, 243501(2013).

Energy chirp control

1.1×10^{19} cm^{-3} | **6×10^{18} cm^{-3}**





Injector+ Accelerator
Energy spread ~ 3 ‰

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

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1. **Background and motivations**
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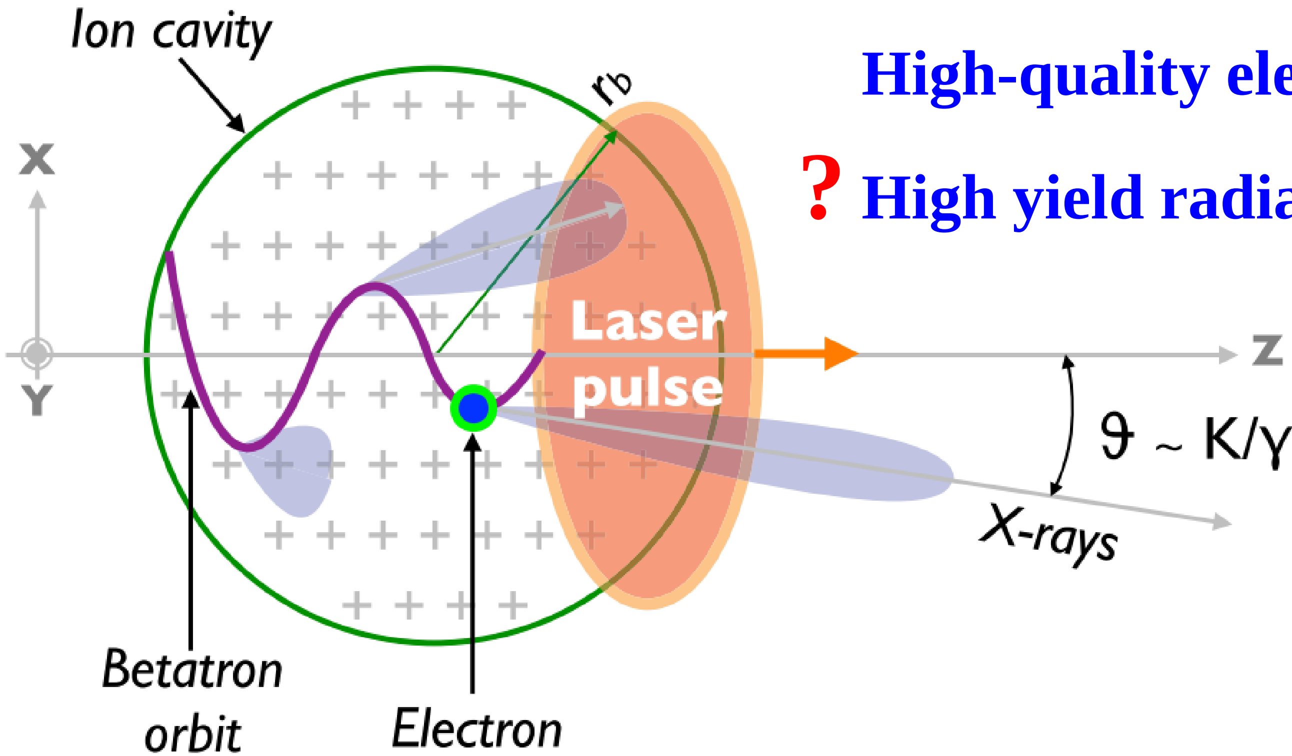
4. **Summary**

I. Betatron radiation enhancement by steering a laser-driven wakefield with a titled shock front



High-quality electron beams

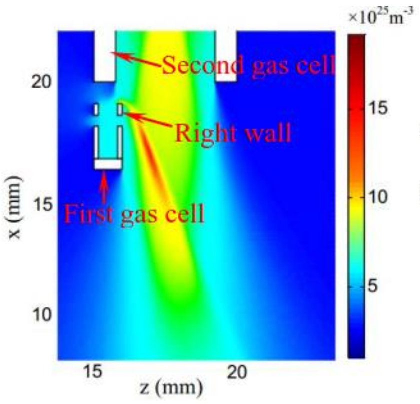
? High yield radiation

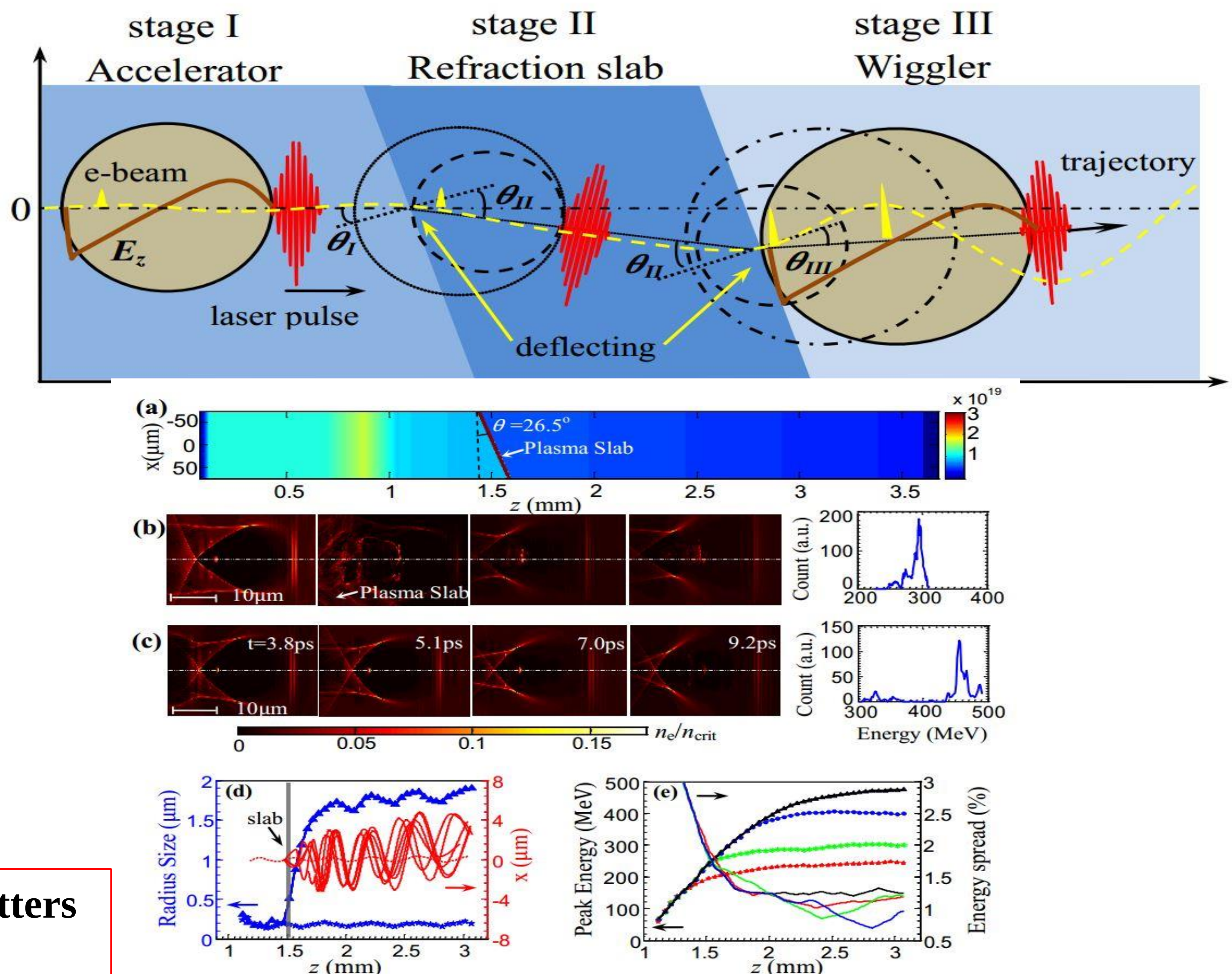
$$K = \gamma \omega_\beta r_\beta / c \simeq 1.33 \times 10^{-10} r_\beta[\mu m] \sqrt{\gamma n_e [cm^{-3}]}$$

$$\hbar\omega_c \approx 5.24 \times 10^{-24} \gamma^2 n_e \left[cm^{-3}\right] r_\beta \left[um\right]$$

$$\langle N_X \rangle = \frac{2\pi e^2}{9\hbar c} N_0 N_e K \approx 5.6 \times 10^{-3} N_0 N_e K$$

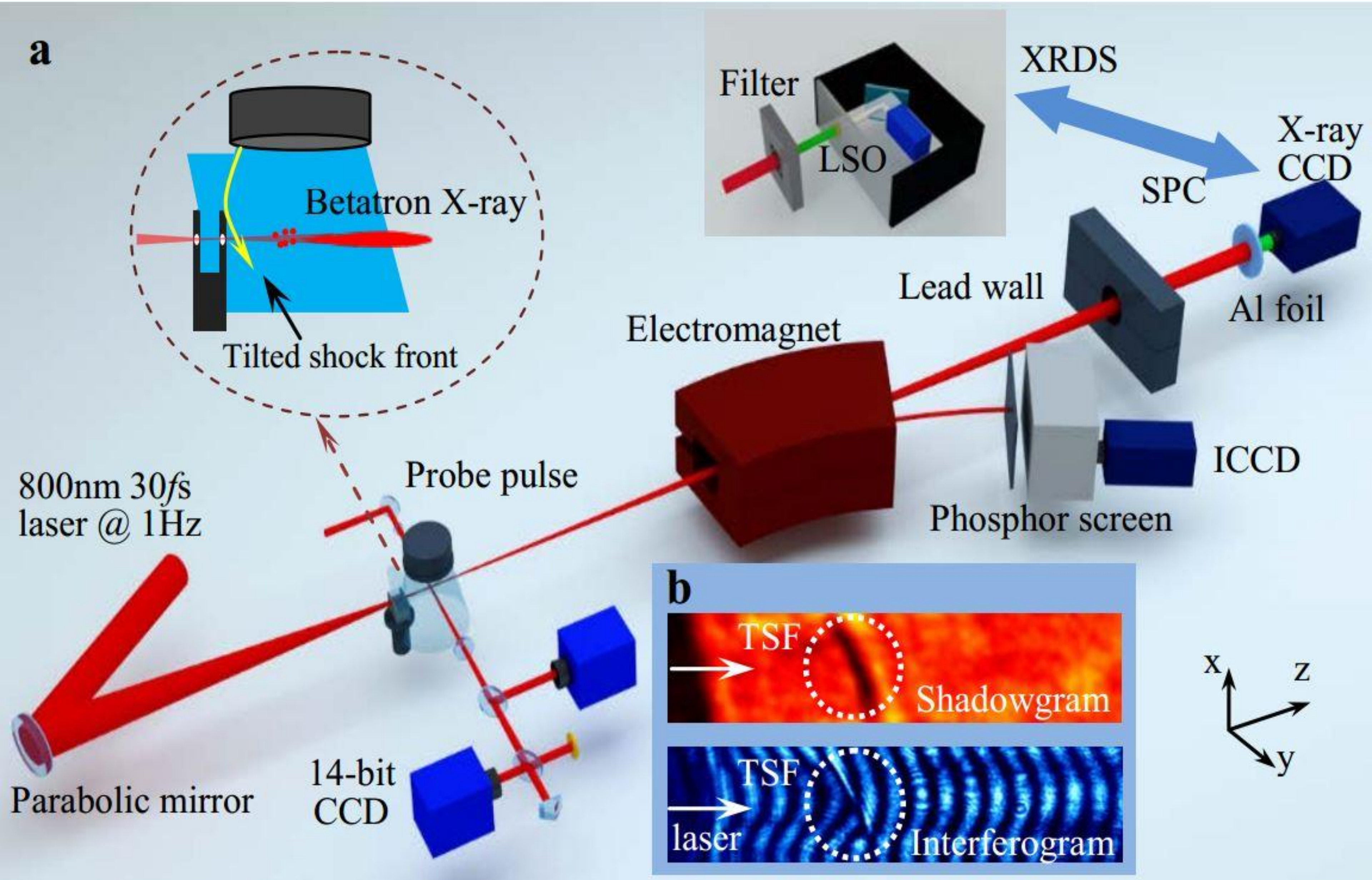
Betatron radiation enhancement by steering a laser-driven wakefield with a titled shock front



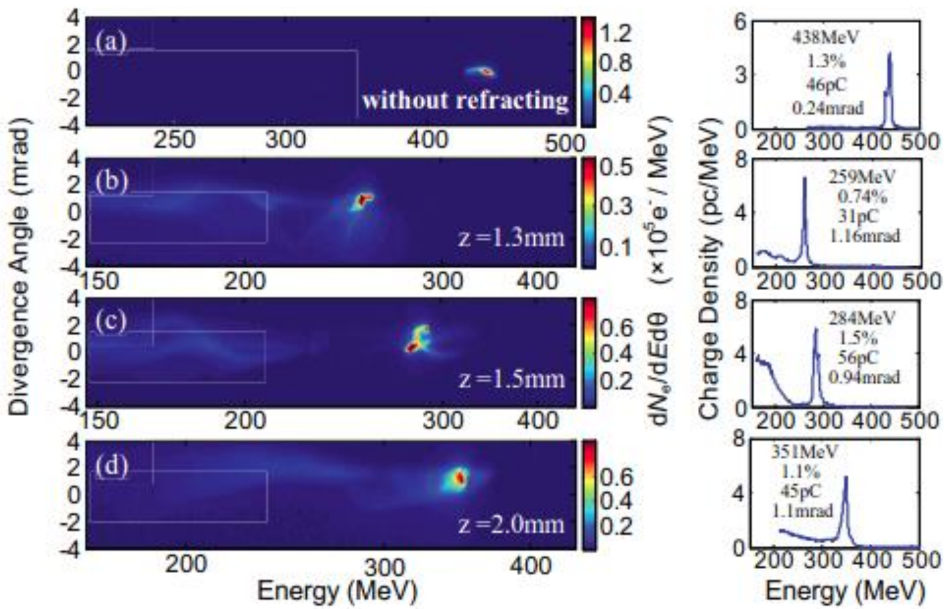


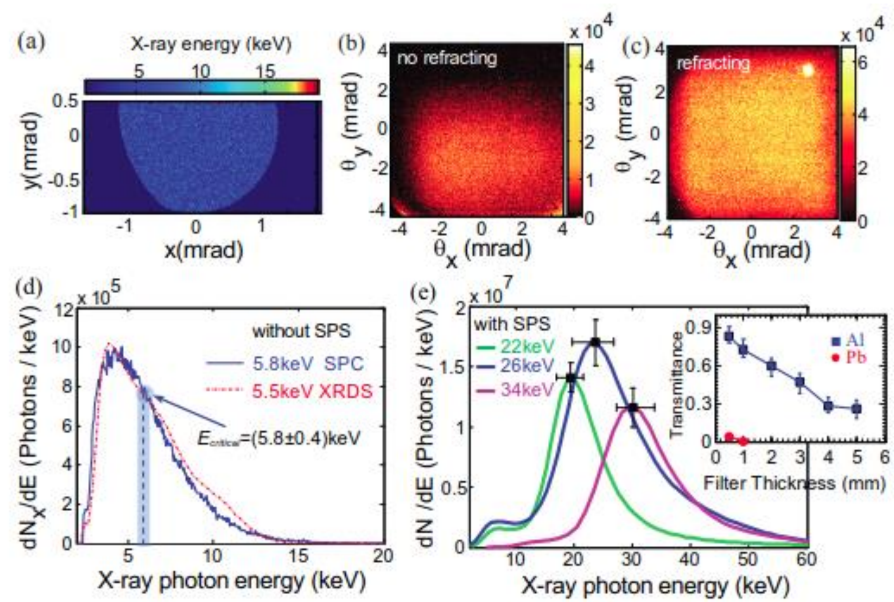
Applied Physics Letters 112, 133503 (2018)

Betatron radiation enhancement by steering a laser-driven wakefield with a titled shock front



Betatron radiation enhancement by steering a laser-driven wakefield with a titled shock front



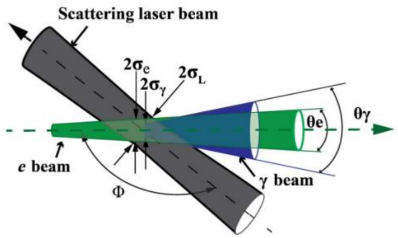


Total x-ray numbers : 2 ×10^{7}. → **Total x-ray numbers :3 ×10^{8}.**

Peak brilliance ~10^{23} photons s^{-1} mm^{-2} mrad^{-2} 0.1% BW.

Applied Physics Letters 112, 133503 (2018)

II. Generation of γ-ray sources via inverse Compton scattering



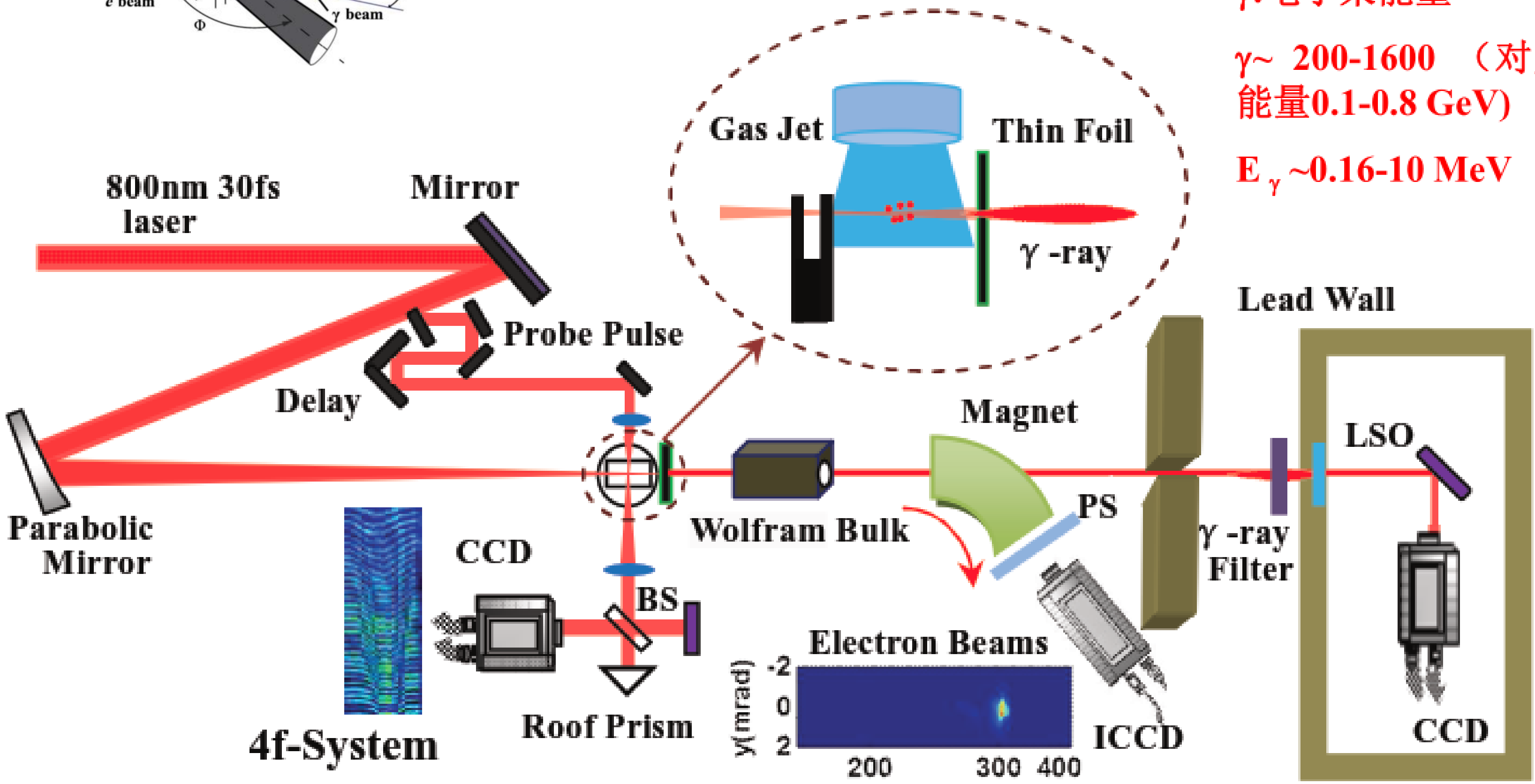
$$E_\gamma = 4\gamma^2 E_L$$

E_L=1.5 eV:激光光子能量

γ:电子束能量

γ~ 200-1600 （对应电子能量0.1-0.8 GeV)

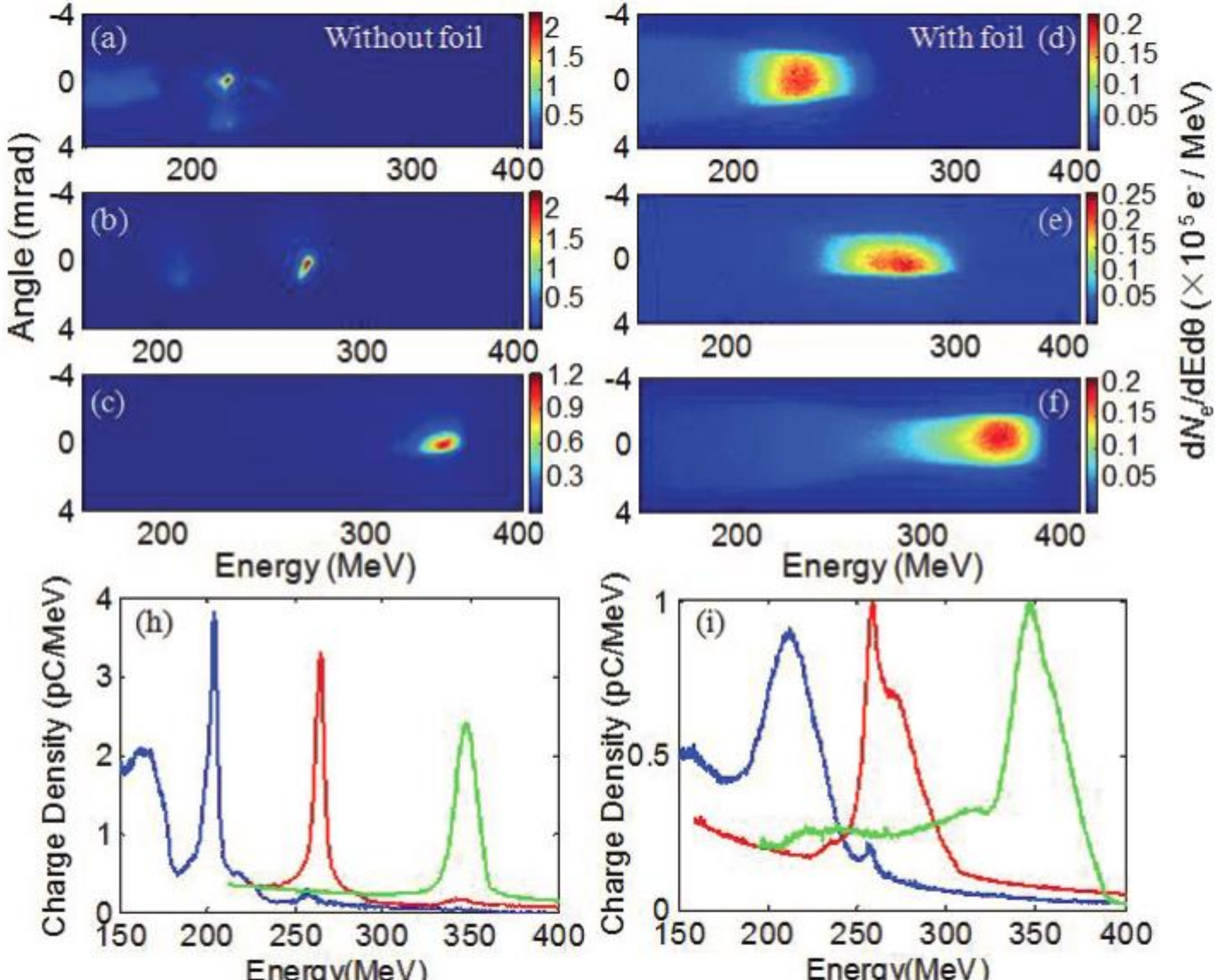
E_γ ~0.16-10 MeV

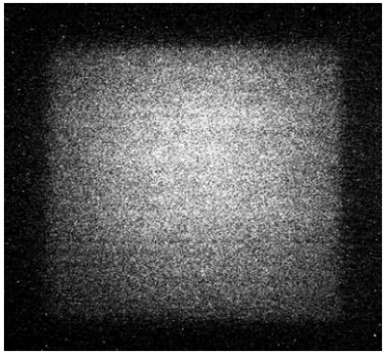


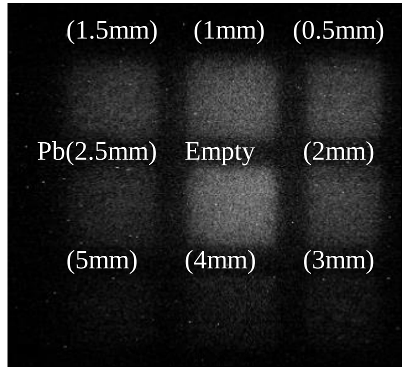
Peak energy: 204 MeV
rms energy spread: 1.2%
Charge: 44 pC
Divergence: 0.48 mrad

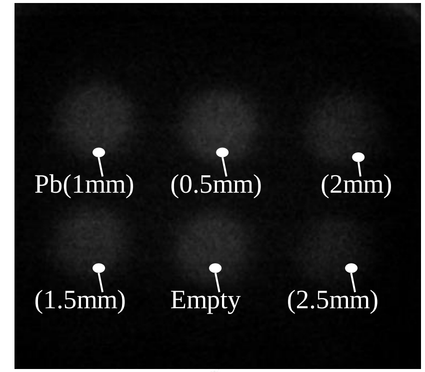
Peak energy: 266 MeV
rms energy spread: 1.1%
Charge: 48 pC
Divergence: 0.75 mrad

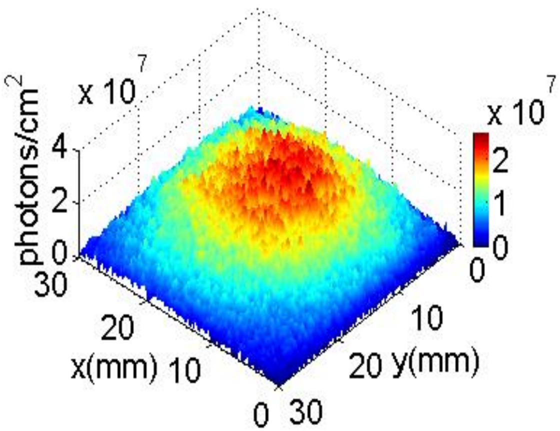
Peak energy: 347 MeV
rms energy spread: 1.7%
Charge: 39 pC
Divergence: 0.71 mrad

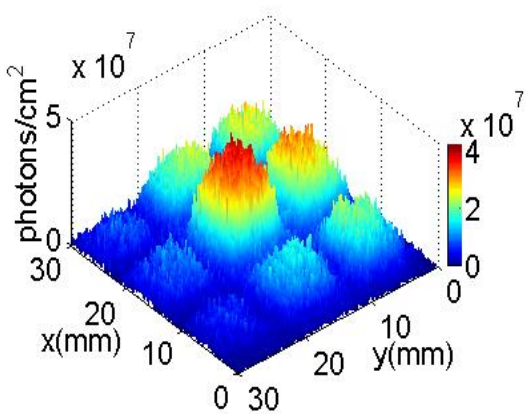


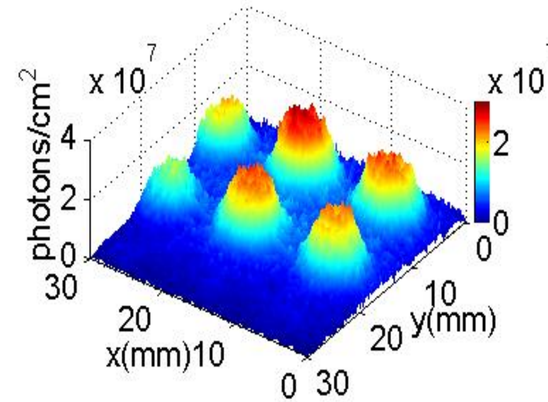


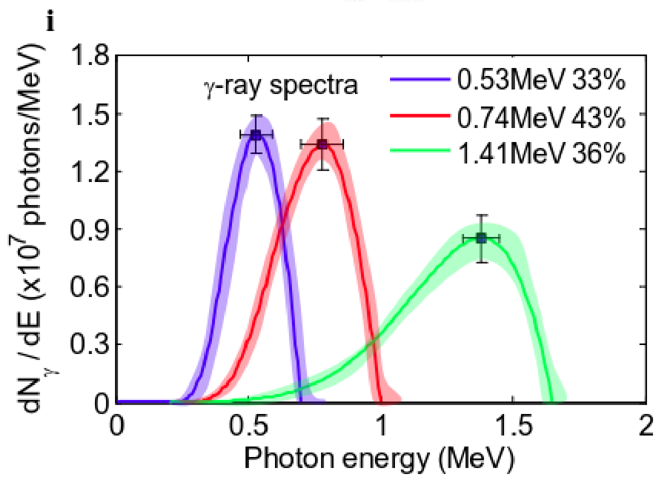












γ-ray yield： 5×10^{7} photons/shot

Divergence： 3.8 mrad × 4.1mrad

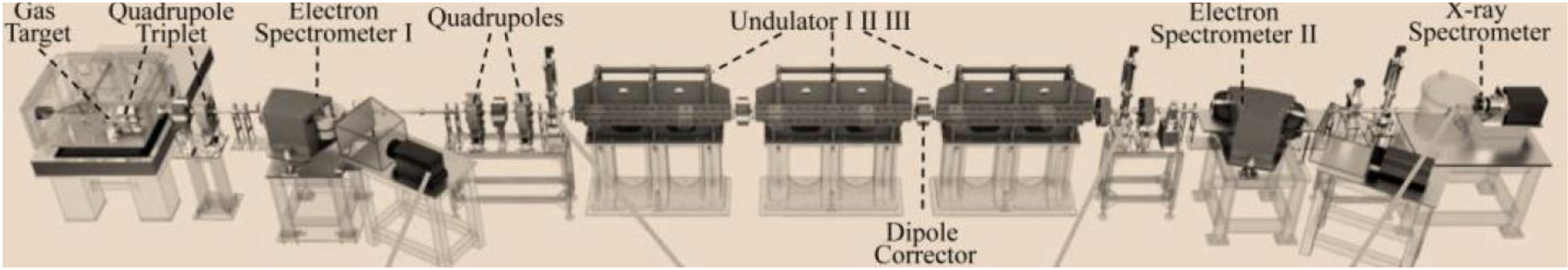
γ-ray duration： $\tau_{ray}^2 = \tau_e^2 + \tau_L^2 / 4\gamma^2 \approx 10\, fs$

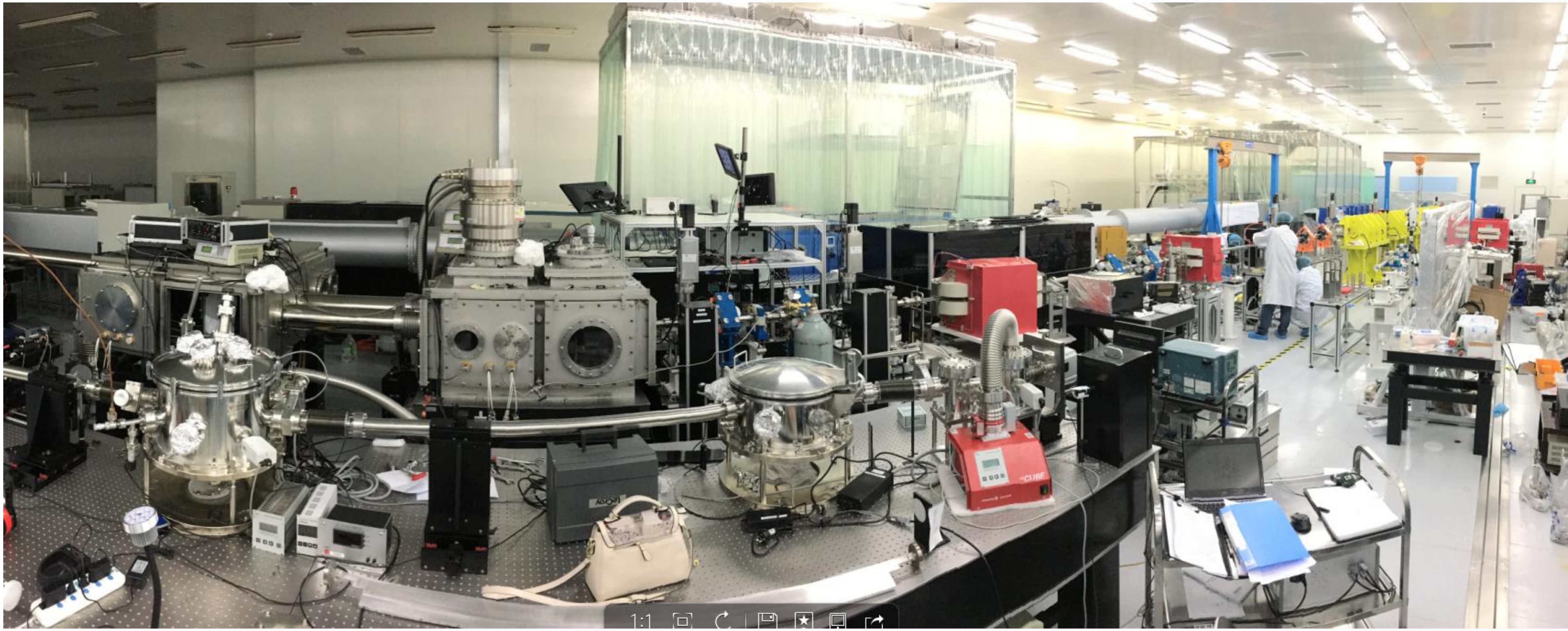
Photons in： 0.1% *BW* 6.5×10^{4} photons

Peak brilliance ~3×10^{22} photons s^{-1} mm^{-2} $mrad^{-2}$ 0.1% BW

[C. Yu *et al.*, Scientific Reports, 6, 29518 (2016)]

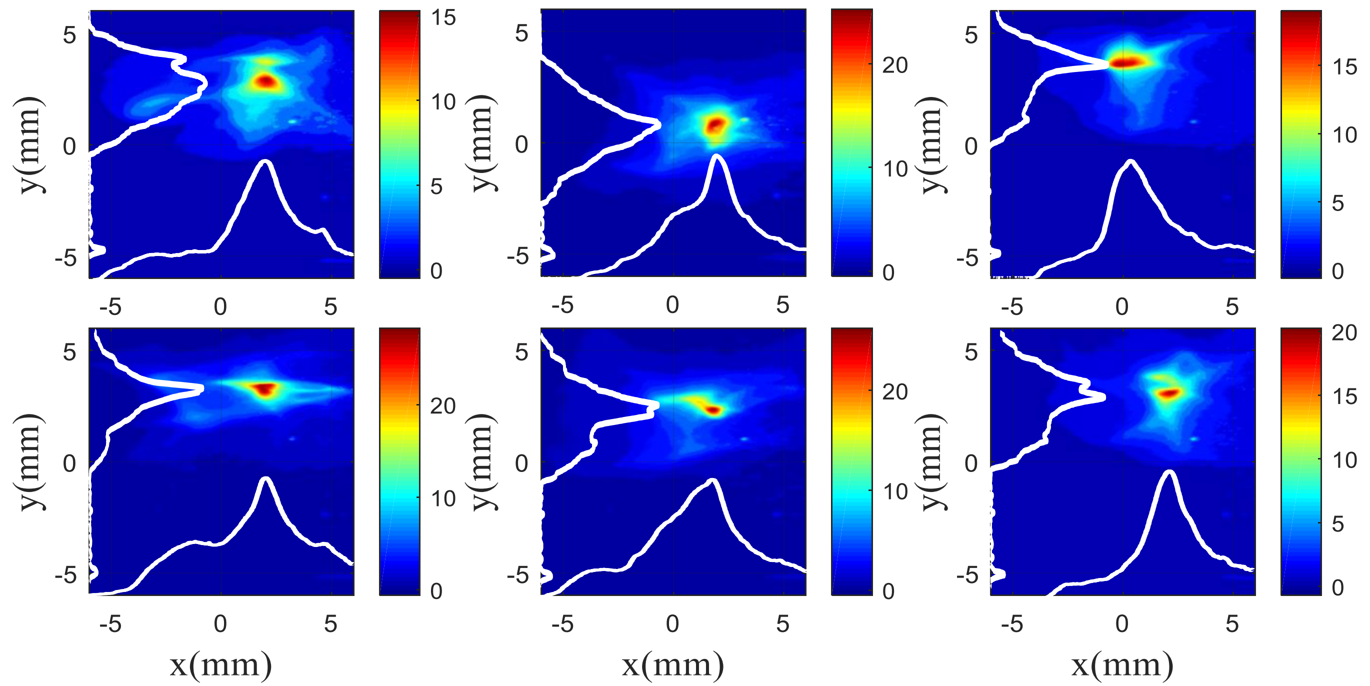
III. X-ray radiation based on a LWFA and an undulator has been demonstrated

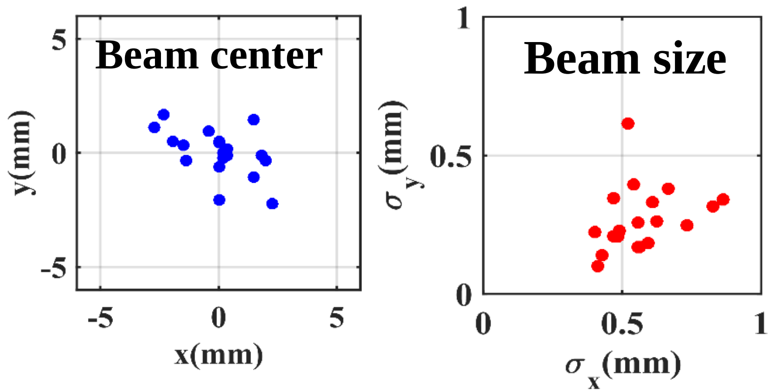




III. X-ray radiation based on a LWFA and an undulator has been demonstrated

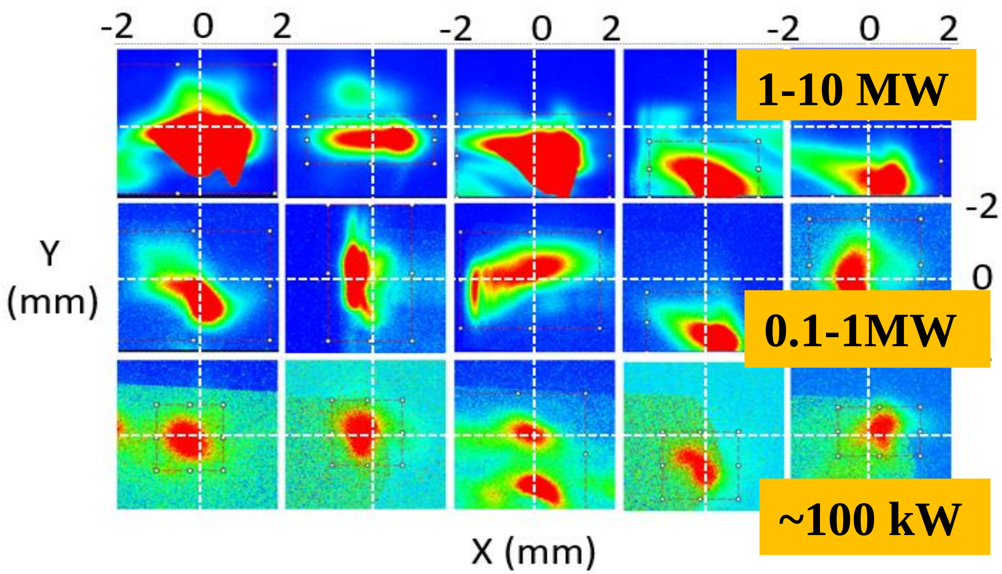
Long-distance transport of e beams from the LWFA into the undulator



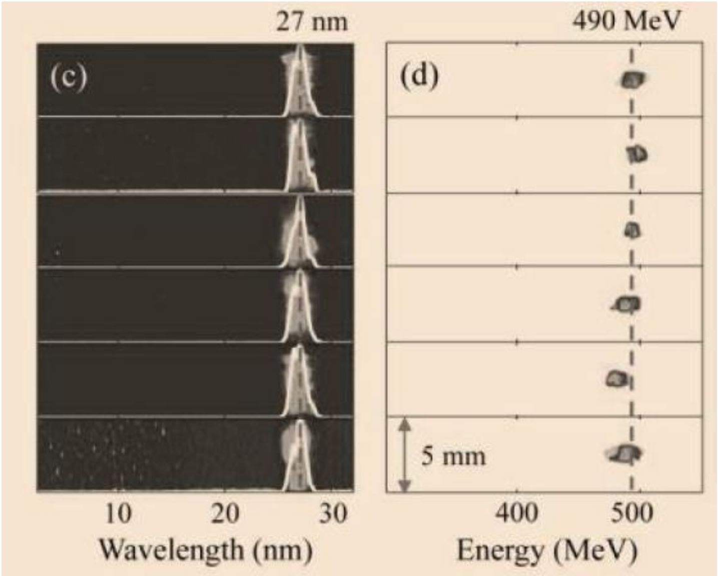


- Beam size can be less than **100 μm**;
- Beam center jitter **~200 μrad**。

III. X-ray radiation based on a LWFA and an undulator has been demonstrated



Measured undulator radiation



Radiation photons : $10^{9\text{-}10}$@27 nm

Summary

- **A two-stage LWFA for generating high-quality electron beams has been experimentally realized. By optimizing the seeding-phase and energy chirp control, high-quality electron beams with an energy spread of few thousandth, small divergence and high stability were produced.**
- **Enhanced betatron radiation was produced by steering a low-energy-spread electron beam in a laser-driven plasma wiggler.**
- **Tunable MeV Gamma-ray Source from Compton Backscattering with ultrahigh brilliance of 3×10^{22} photons s^{-1} mm^{-2} $mrad^{-2}$ 0.1% BW has been experimentally demonstrated.**
- **A XFEL platform based on the LWFA electron-beams and an undulator has been installed and tested. X-ray radiation at 27 nm has been observed.**

Thank you for your attention!