



上海交通大学

SHANGHAI JIAO TONG UNIVERSITY



Novel laser-plasma electron acceleration experiments @ SJTU based on ionization injection and two-color laser pulses

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Electron Acceleration Team @SJTU

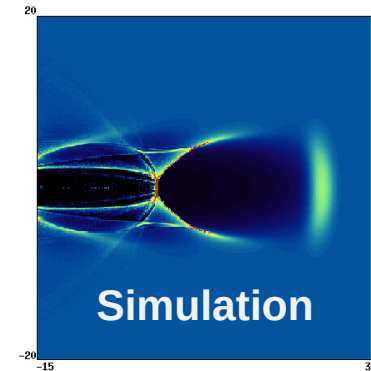
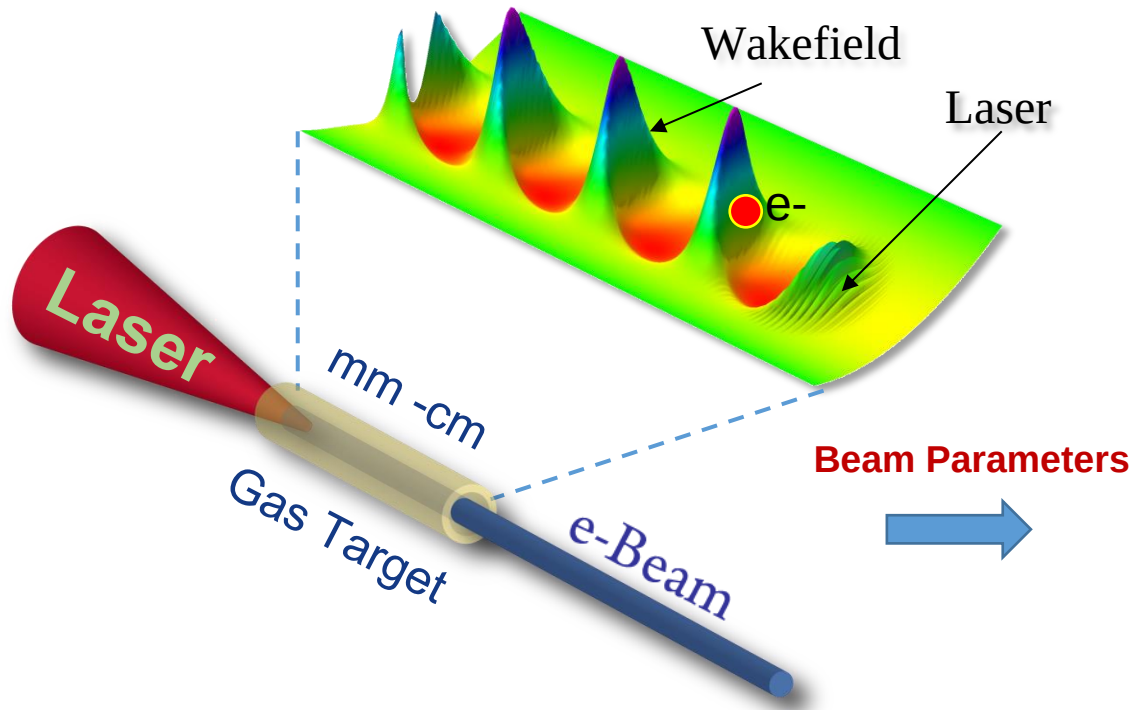


Main Topics & Motivation

- ④ **Towards compact FELs: narrow energy-spread electron beams (SJTU)**
 - Next-generation compact XFELs and colliders
- ④ **X-ray sources: radiation due to betatron motion (SJTU, CAS & LLNL)**
 - 10 Hz desk-top ultrafast synchrotron radiation applications (phase-contrast imaging, x-ray diffraction etc.)
- ④ **Compact secondary radiation sources (SJTU)**
 - Compact positron and gamma-ray source. Important for applications in condensed-matter physics, radiography and nuclear physics.
 - 10 Hz source has a potential for applications.
- ④ **Summary and Conclusions**

- Laser intensity $I = 10^{18-19} \text{ W/cm}^2$
- Gas (plasma) density: $n_e = 10^{18-19} \text{ cm}^{-3}$
- ($E_z \sim 1 \text{ GV/cm}$, $v_p \sim c$)
- $\lambda_p \sim \text{tens } \mu\text{m}$ (good and bad)

[Tajima and Dawson, PRL \(1979\)](#)



Divergence	few mrad
Bunch length	< 10 fs
Charge	10-100 pC
Energy spread	Tens %
Energy	Up to Multi-GeV



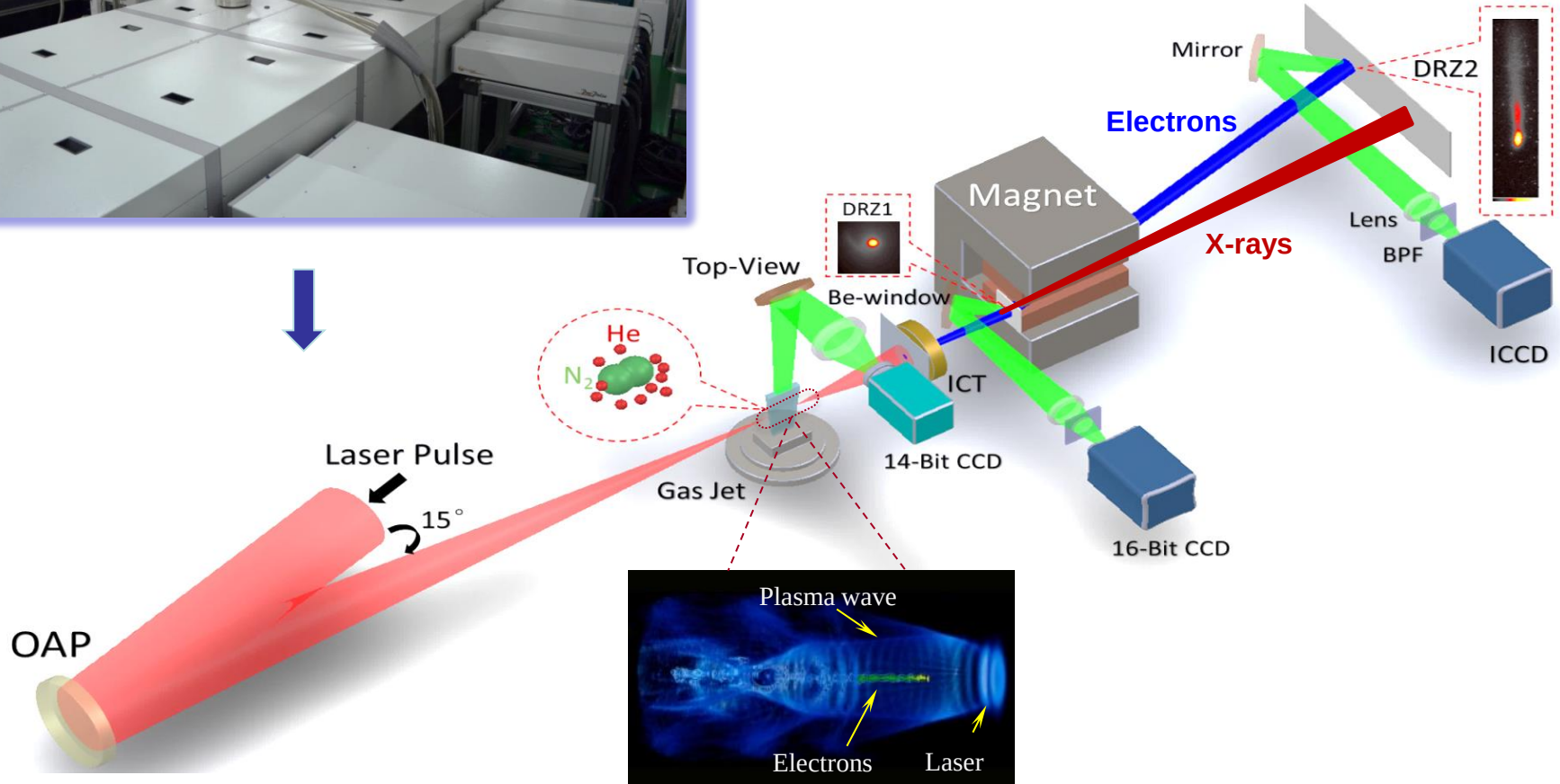
Laser System for Laser-Plasma Acceleration



(AT) 200 TW, 30 fs Laser System @ SJTU

(typically: 30-60 TW is for experiments)

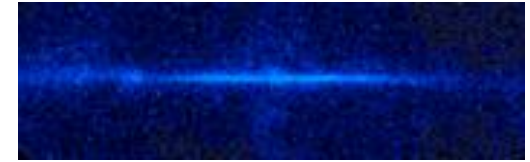
(120 TW was used in 1 expt.)



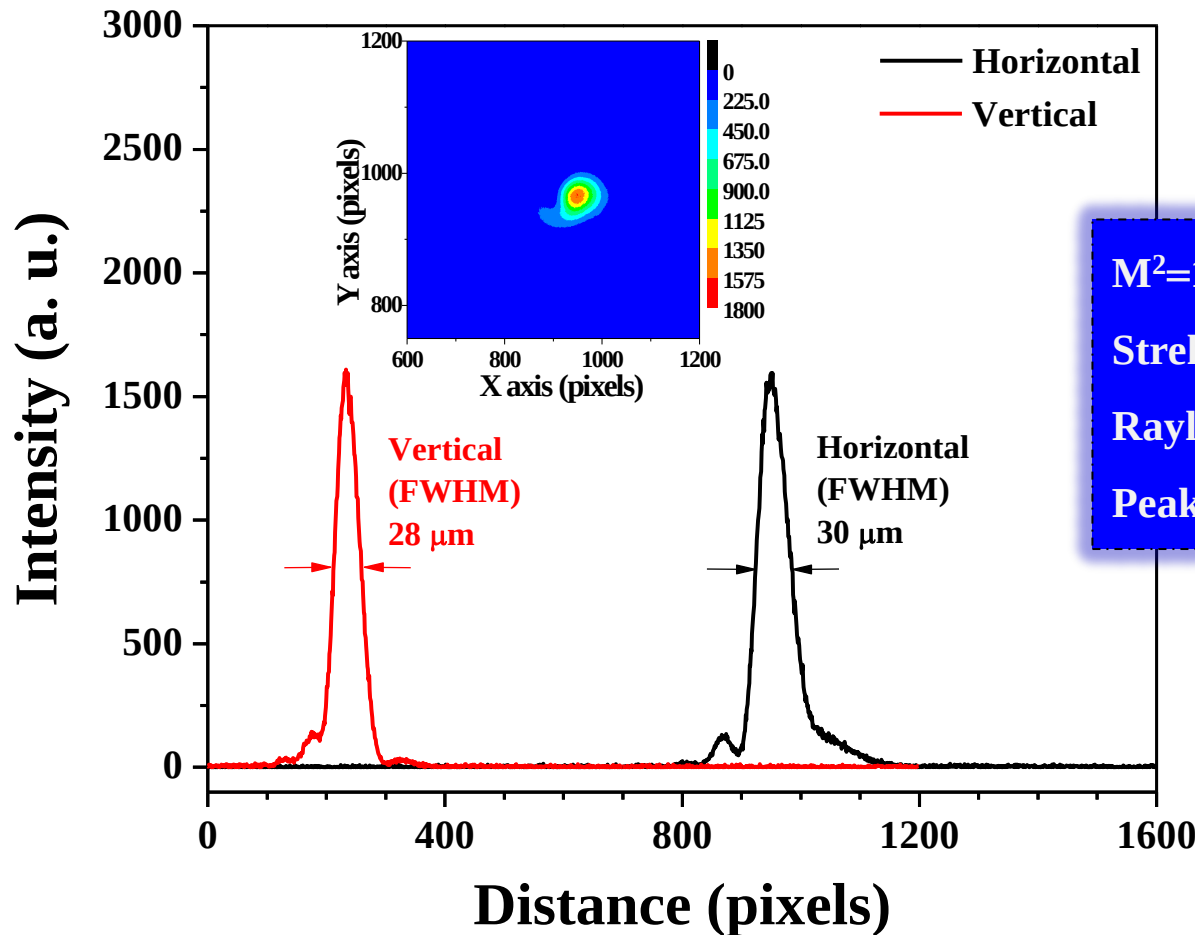


Laser Focal Spot with f/21 OAP

We have to use long focusing for cm-scale acceleration length



≤ 1 cm- long (gas) plasma



$$M^2=1.6$$

Strehl Ratio: 0.4–0.5

Rayleigh length: $Z_r=3$ mm

Peak laser intensity: $2\sim 9 \times 10^{18} \text{ W.cm}^{-2}$

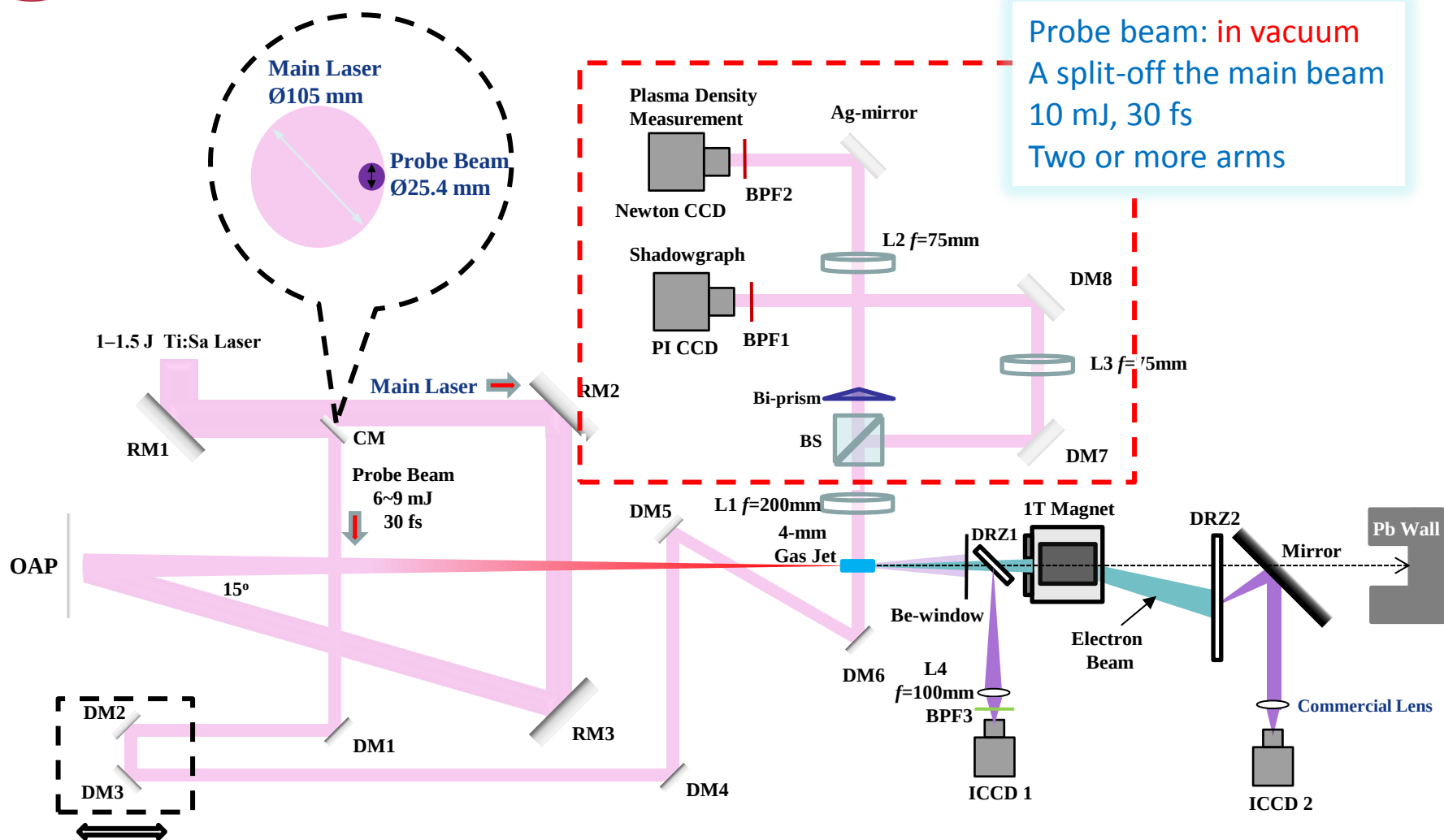
$$2w_{1/e} = M^2 \frac{1.78\lambda f}{D}$$

Expected: Laser spot size : 20 μm (the problem is the large M^2)

Currently: we do not have adaptive optics for corrections.



Time-resolved Plasma Diagnostics-Setup



Probe beam: in vacuum
A split-off the main beam
10 mJ, 30 fs
Two or more arms

Probe Beam Delay System
Time-resolution: ~30 fs

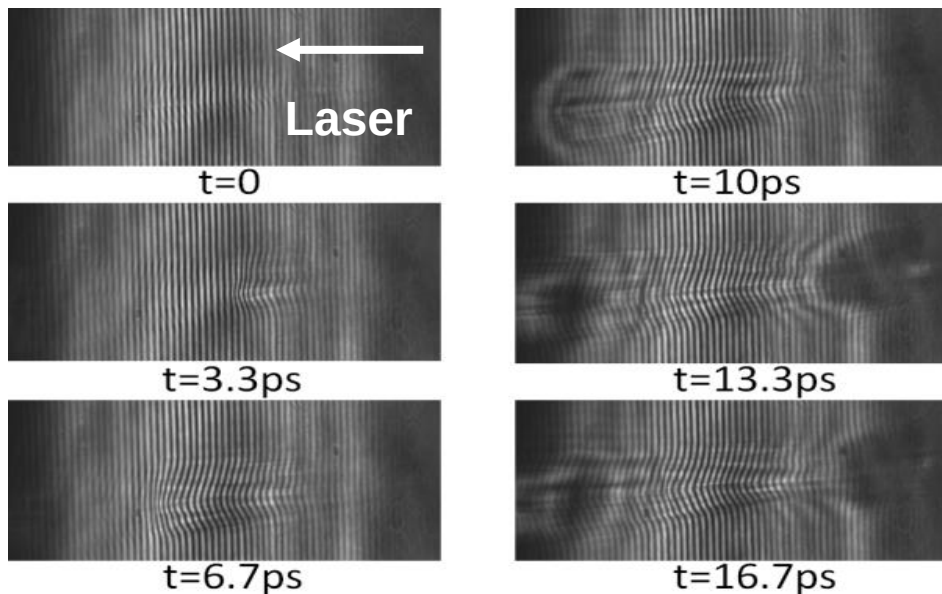
Time-resolved Plasma Diagnostics-Results

Laser: 30 TW, 30 fs

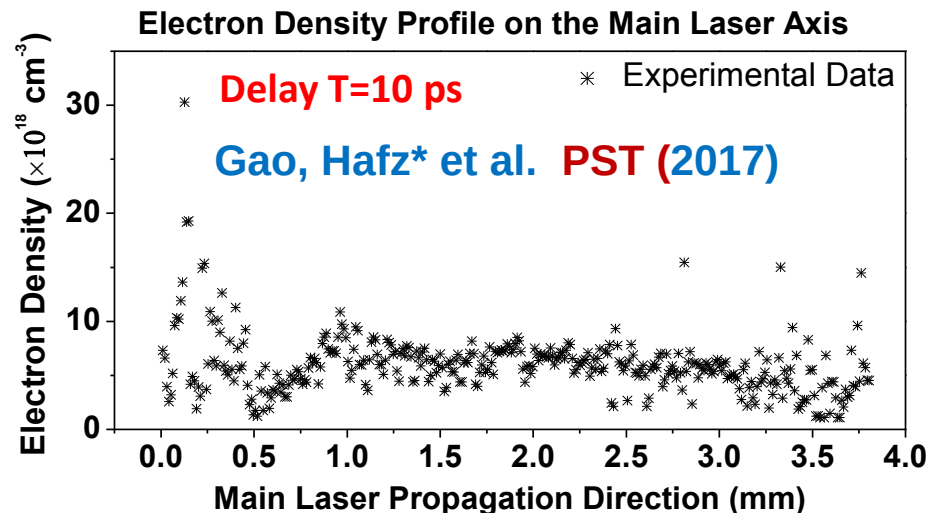
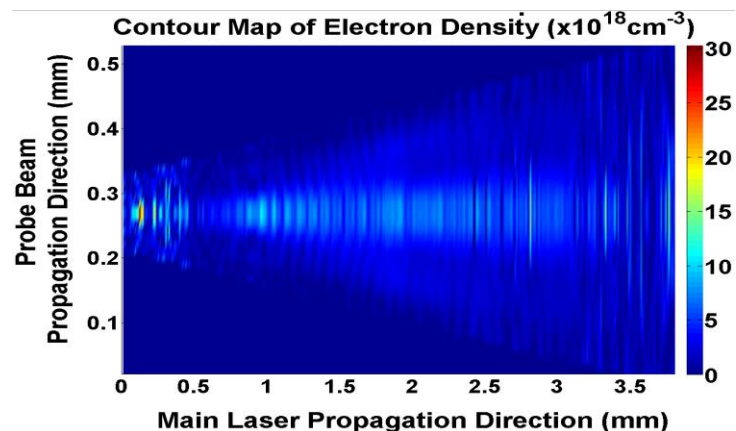
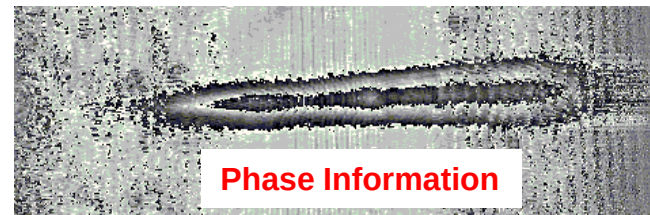
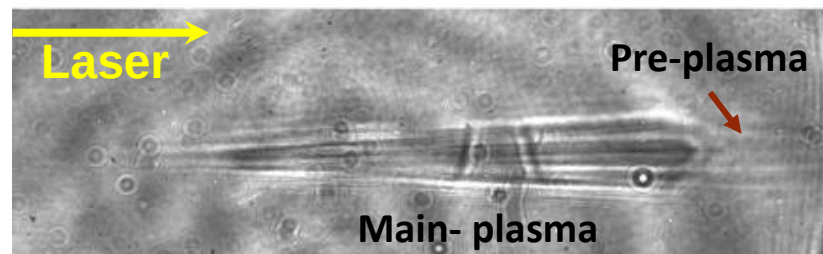
Gas Nozzle: 4 mm mixing gas Jet

Focal Spot Size: $w_0 = 30 \mu\text{m}$

Probe beam: 30 fs

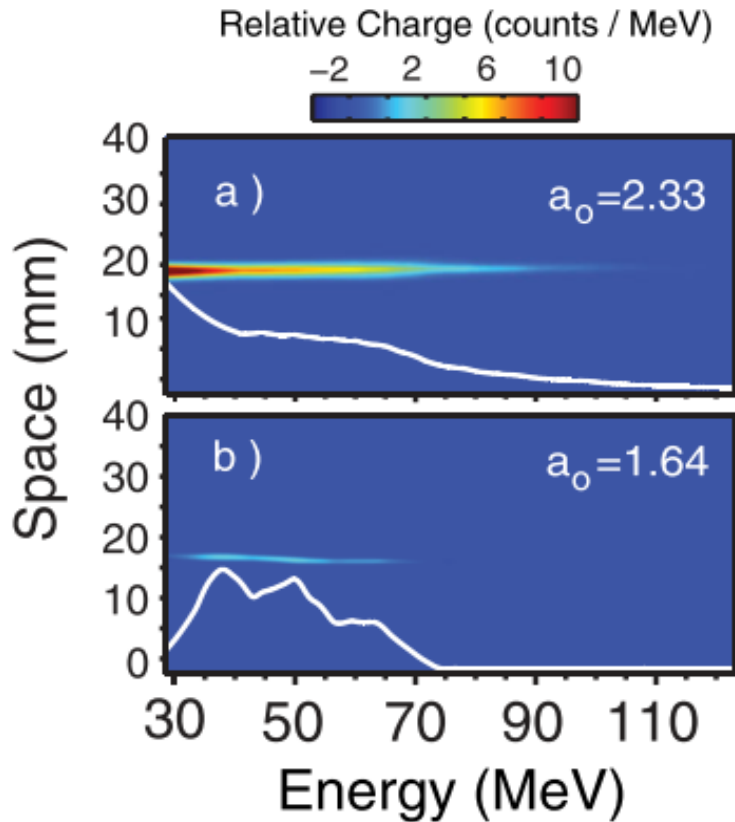


Shadowgraph



Ionization-induced Electron Injection in gas mixture (He+10%N₂)

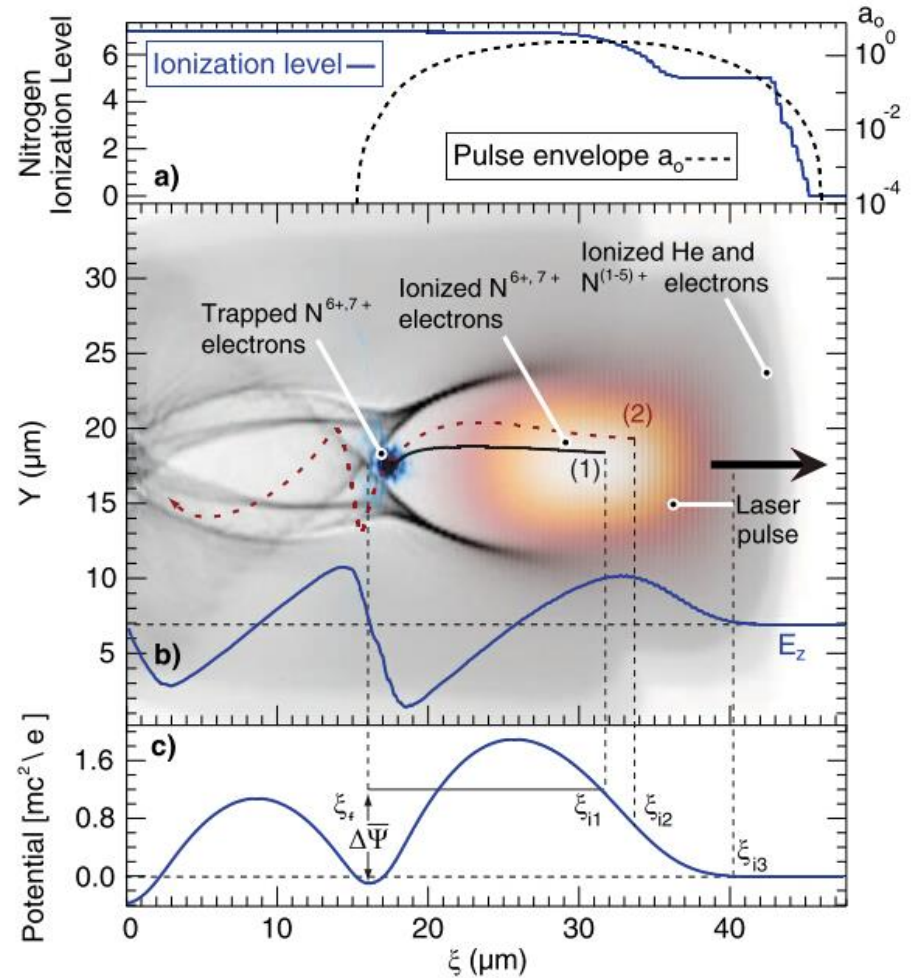
A. Pak *et al.* PRL(2010)



Matching condition for stable bubble

$$k_p w_0 \sim 2\sqrt{a_0}$$

Trapping condition: $|\Delta\Psi| \gtrsim 1$

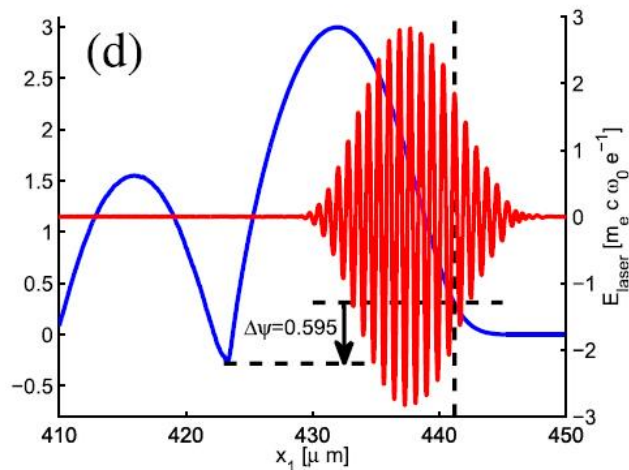
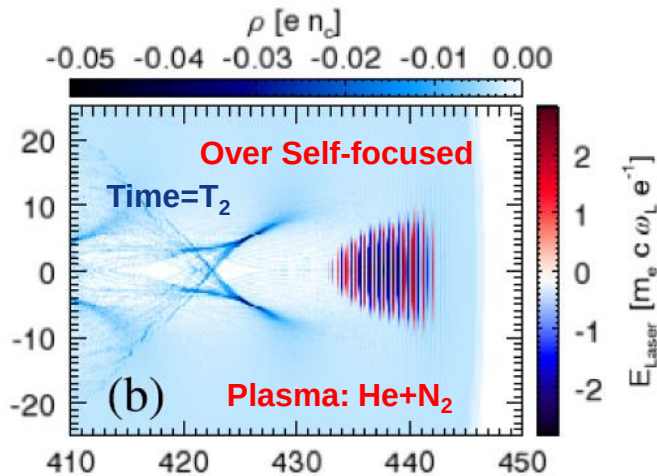


$$\Psi \equiv \Phi - \frac{V_\phi}{c} A_z$$

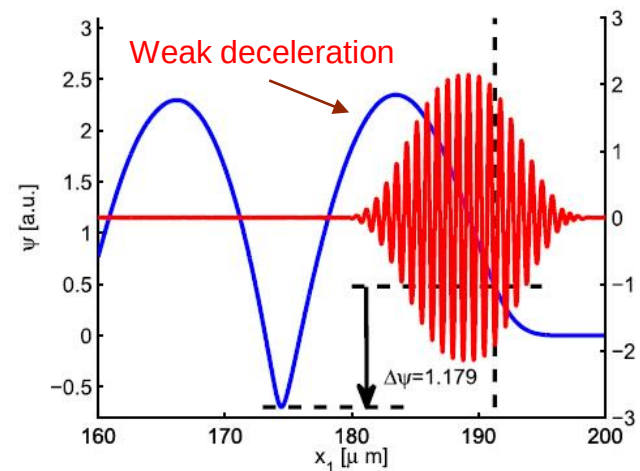
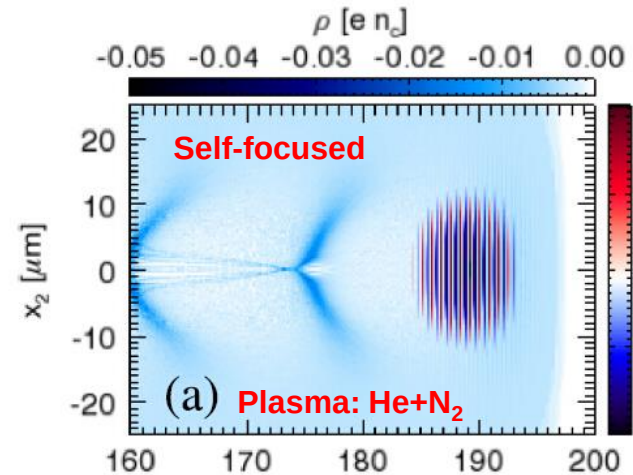


Self-truncated Ionization Injection (STII): High-quality, Narrow-Energy Spread Electron Beams

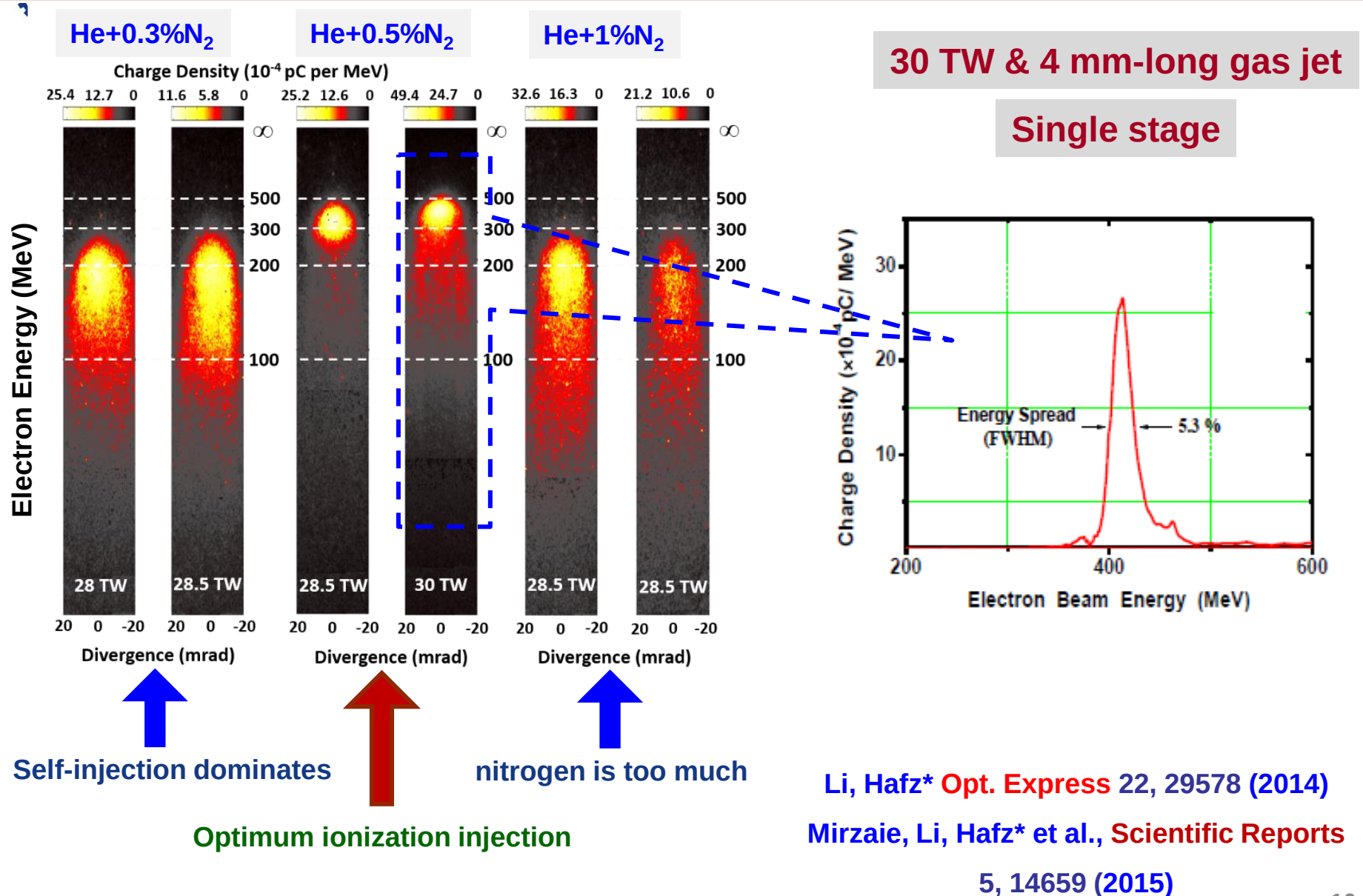
$$k_p w_0 = 7.6 > 2\sqrt{a_0} = 2.8$$



Trapping condition: $|\Delta\Psi| \gtrsim 1$



Controlling energy-spread via the N₂ concentration



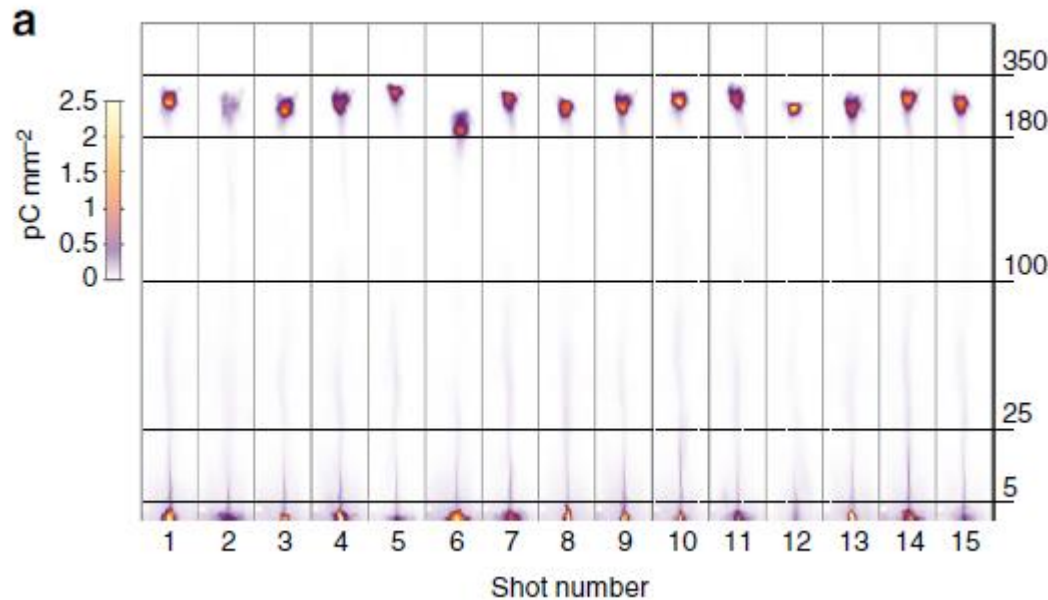
Li, Hafz* *Opt. Express* 22, 29578 (2014)

Mirzaie, Li, Hafz* et al., *Scientific Reports*

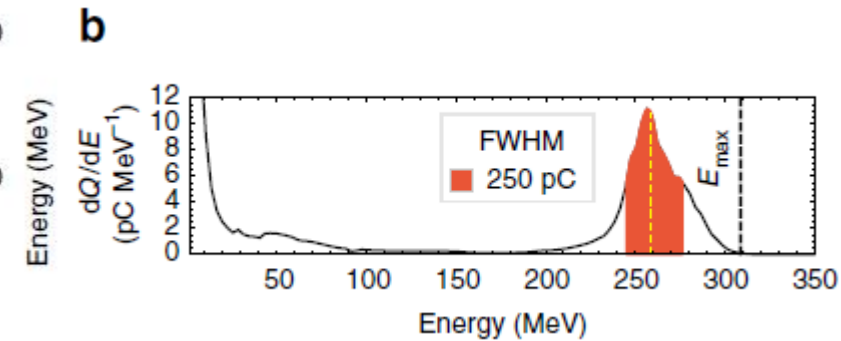
5, 14659 (2015)



Beam loaded n C-class Laser-Plasma Accelerator

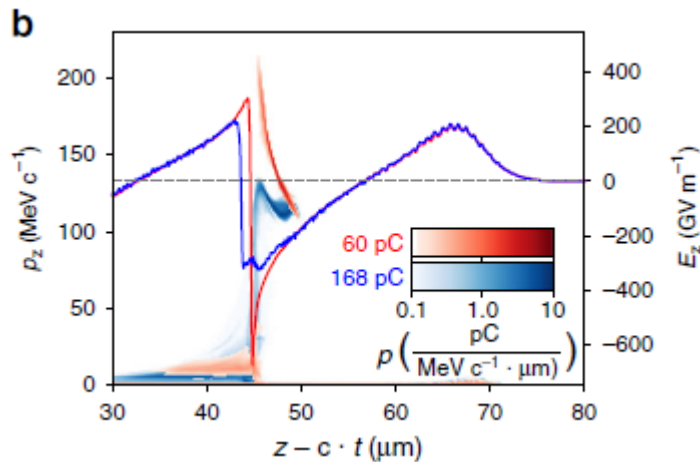


J. Couperus et al *Nat. Comm.*8, 487(2017)



Abstract

Laser-plasma wakefield accelerators have seen tremendous progress, now capable of producing quasi-monoenergetic electron beams in the GeV energy range with few-femtoseconds bunch duration. Scaling these accelerators to the nanocoulomb range would yield hundreds of kiloamperes peak current and stimulate the next generation of radiation sources covering high-field THz, high-brightness X-ray and γ -ray sources, compact free-electron lasers and laboratory-size beam-driven plasma accelerators. However, accelerators generating such currents operate in the beam loading regime where the accelerating field is strongly modified by the self-fields of the injected bunch, potentially deteriorating key beam parameters. Here we demonstrate that, if appropriately controlled, the beam loading effect can be employed to improve the accelerator's performance. Self-truncated ionization injection enables loading of unprecedented charges of ~ 0.5 nC within a mono-energetic peak. As the energy balance is reached, we show that the accelerator operates at the theoretically predicted optimal loading condition and the final energy spread is minimized.





Demonstration of STII for GeV electron beams

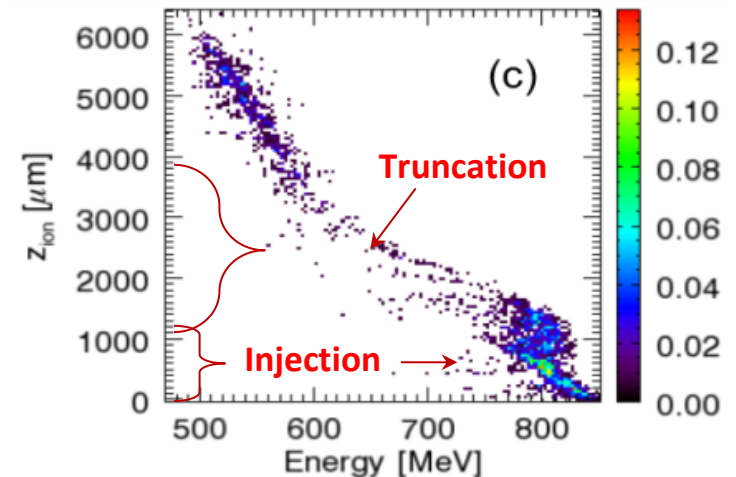
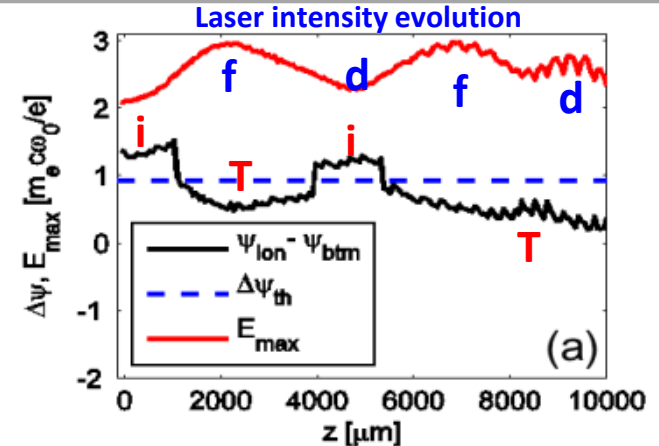
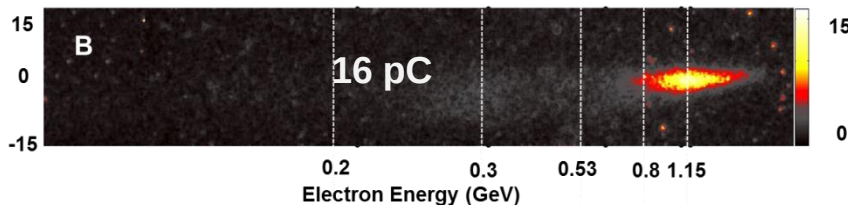
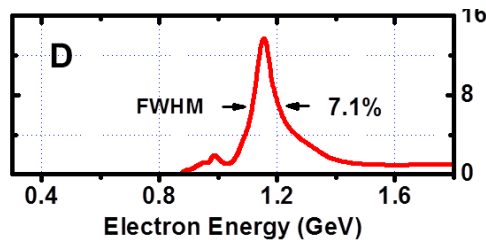
118 TW & 1 cm gas jet

Single stage

2D-PIC-Simulations

Experimental results

Ionization-injection in He+0.3% N₂



Li, Hafz* **Opt. Express** 22, 29578 (2014)

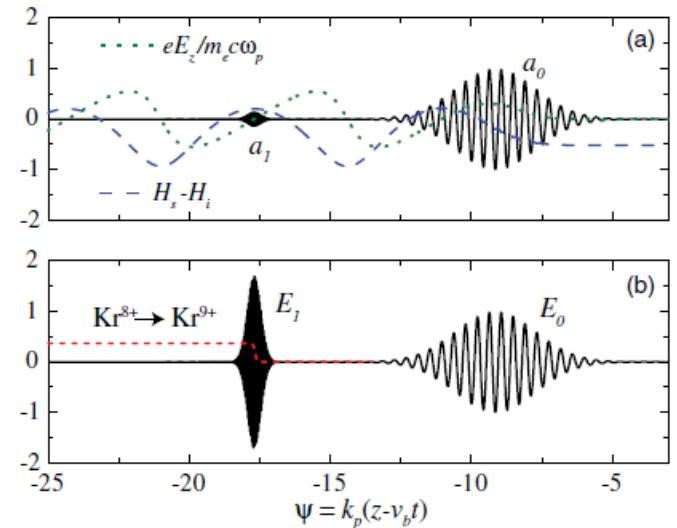
Mirzaie, Hafz* **Scientific Reports** 5, 14659 (2015)

Two-Color Laser-Ionization Injection

L.-L. Yu,^{1,2,3} E. Esarey,¹ C. B. Schroeder,¹ J.-L. Vay,¹ C. Benedetti,¹ C. G. R. Geddes,¹ M. Chen,³ and W. P. Leemans^{1,2}¹Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA²Department of Physics, University of California, Berkeley, California 94720, USA³Key Laboratory for Laser Plasmas (Ministry of Education), Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

(Received 31 July 2013; published 24 March 2014)

A method is proposed to generate femtosecond, ultralow emittance ($\sim 10^{-8}$ m rad), electron beams in a laser-plasma accelerator using two lasers of different colors. A long-wavelength pump pulse, with a large ponderomotive force and small peak electric field, excites a wake without fully ionizing a high-Z gas. A short-wavelength injection pulse, with a small ponderomotive force and large peak electric field, copropagates and delayed with respect to the pump laser, ionizes a fraction of the remaining bound electrons at a trapping wake phase, generating an electron beam that is accelerated in the wake.



Multichromatic Narrow-Energy-Spread Electron Bunches from Laser-Wakefield Acceleration with Dual-Color Lasers

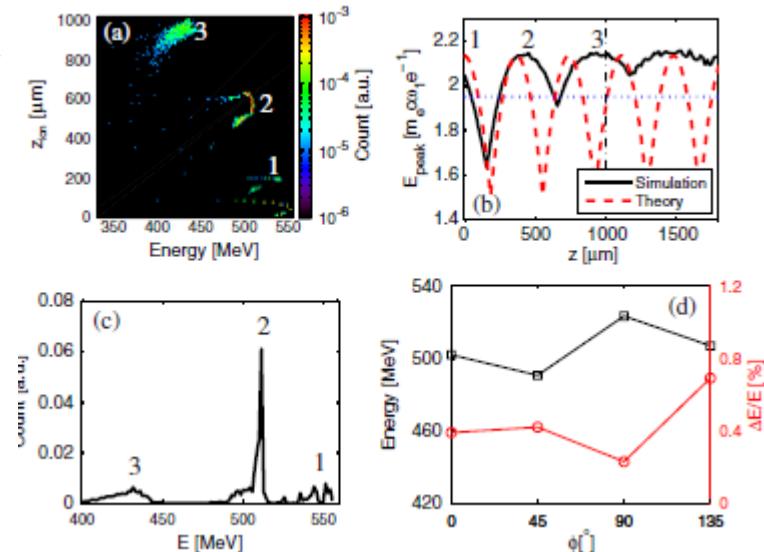
M. Zeng,^{1,2} M. Chen,^{1,2,*} L. L. Yu,^{1,2} W. B. Mori,³ Z. M. Sheng,^{1,2,4,\dagger} B. Hidding,⁴ D. A. Jaroszynski,⁴ and J. Zhang^{1,2}¹Key Laboratory for Laser Plasmas (Ministry of Education), Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China²IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China³University of California, Los Angeles, California 90095, USA⁴SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom

(Received 30 June 2014; published 24 February 2015)

A method based on laser wakefield acceleration with controlled ionization injection triggered by another frequency-tripled laser is proposed, which can produce electron bunches with low energy spread. As two color pulses copropagate in the background plasma, the peak amplitude of the combined laser field is modulated in time and space during the laser propagation due to the plasma dispersion. Ionization injection occurs when the peak amplitude exceeds a certain threshold. The threshold is exceeded for limited duration periodically at different propagation distances, leading to multiple ionization injections and separated electron bunches. The method is demonstrated through multidimensional particle-in-cell simulations. Such electron bunches may be used to generate multichromatic x-ray sources for a variety of applications.

DOI: 10.1103/PhysRevLett.114.084801

PACS numbers: 29.25.Bx, 41.75.Jv, 42.55.Vc, 82.53.-k

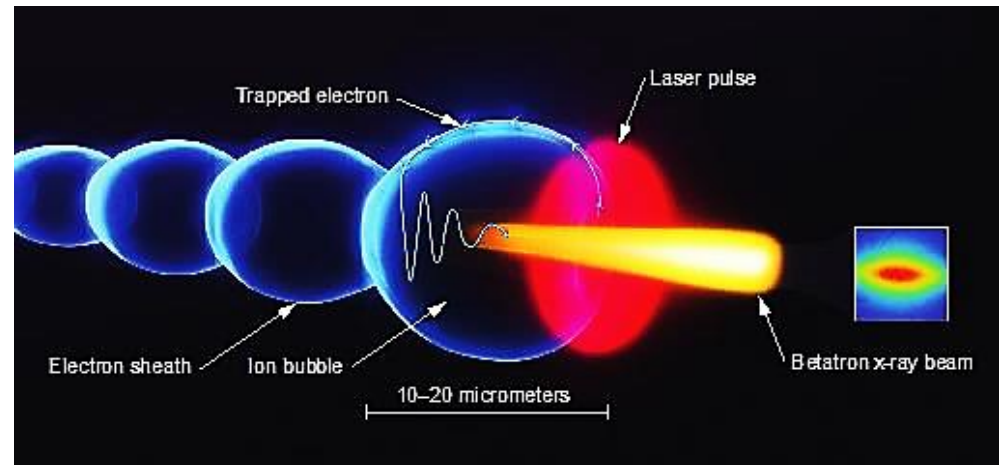


Incoherent X-ray generation - betatron (wiggler) radiation

Betatron X-ray radiation

(S. Cipiccia et al., Strathclyde)
(F. Albert: LLNL)

Plasma wiggler (synchrotron)



Advantage:

- Table-top source
- 10^{6-7} photons/pulse
- Few mrad divergence
- μm source size
- femtosecond duration
- perfect synchronization.

Applications:

- phase contrast imaging
- X-ray absorption spectroscopy
- X-ray Diffraction
- pump-probe experiments



Ionization injection generates brighter X-ray yields

A 10 Hz X-ray source is attractive for applications

Betatron X-ray radiation

(S. Cipiccia et al.,
Strathclyde)

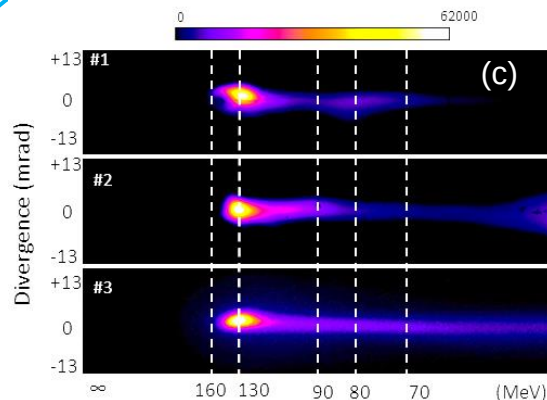
(F. Albert: LLNL)

Yan et al. Hafz et al., **PNAS** 111, 5825(2014)

Huang et al. Hafz et al., Scientific Reports 6, 27633 (2016)

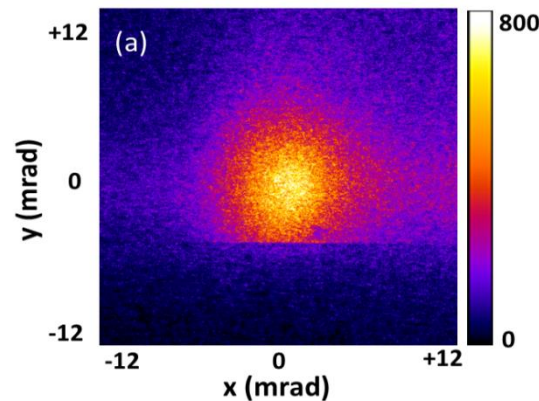
Huang, Hafz et al., Appl. Phys. Lett. 105, 204101 (2014)

60 TW & 4 mm-long N₂ gas jet



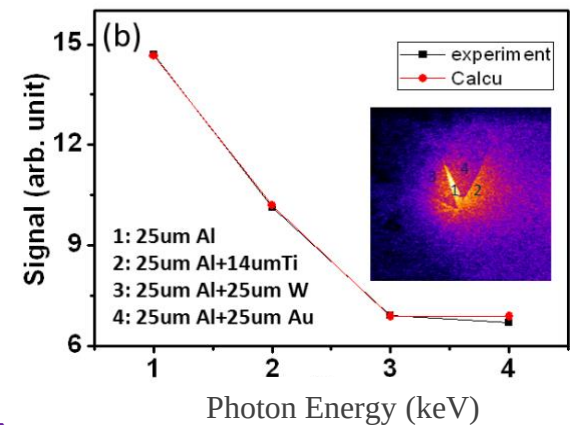
Electron Energy

(with ionization injection)



X-ray profile ($10^7 \sim 10^8$ photons)

Particularly enhanced yield due to emission by a high current beams



X-ray spectrum



Applications of our electron beams

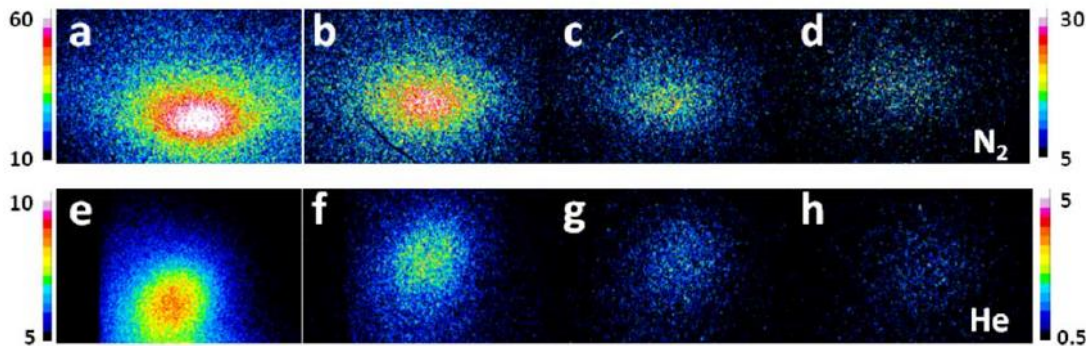
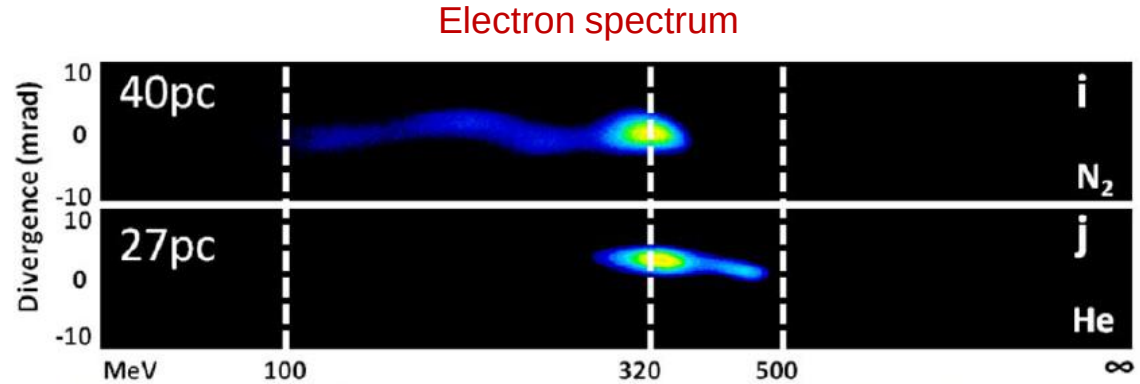
☐ Laser:

Peak Power: 120 TW, $a_0 > 2$

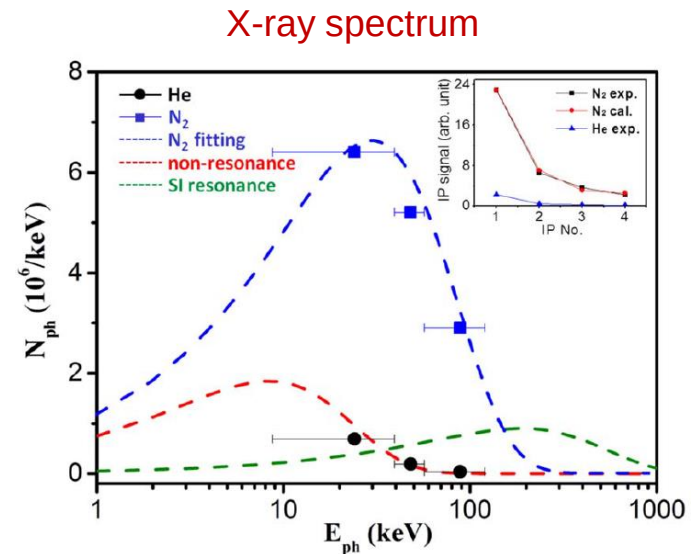
Focal spot size: $w_0 = 28 \mu\text{m}$

☐ Gas Jet: 10 mm

Nitrogen gas jet



X-ray profile (10^8 photons/pulse)





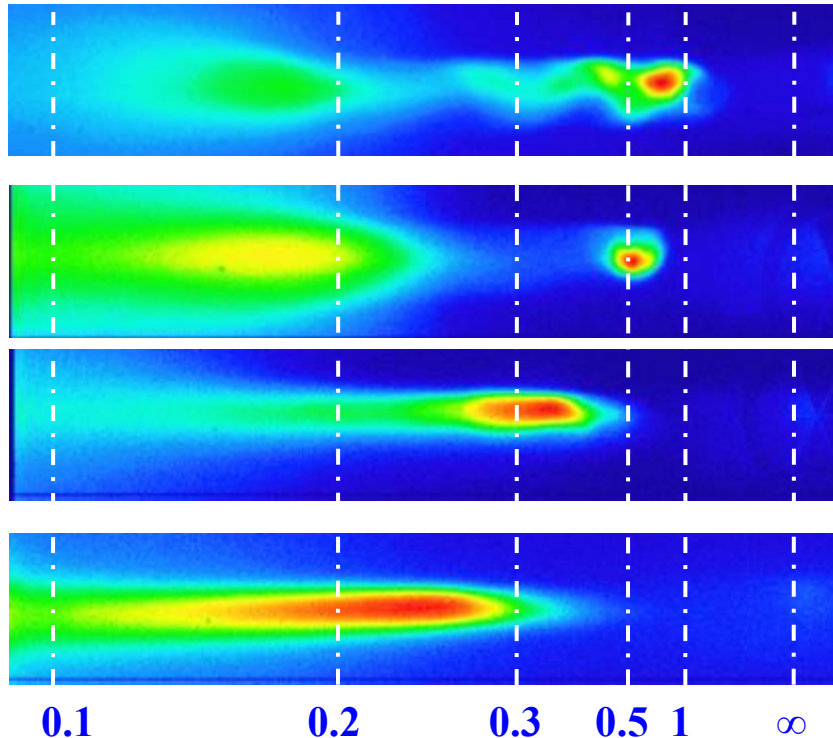
LWFA & Betatron X-rays in 1cm He gas jet

Y. Ma, L. Chen*, Hafz (APL 2014)

W. C. Yan, L. Chen*, Hafz (PNAS 2014)

LLNL Calisto Laser: 120 TW

Electrons Energy Spectrum



Electron energy (GeV)

P~125 TW

Pressure= 32 psi

$E_{\text{peak}} \sim 0.8$ GeV

P~103 TW

Pressure= 30 psi

$E_{\text{peak}} \sim 0.5$ GeV

P~70 TW

Pressure= 35 psi

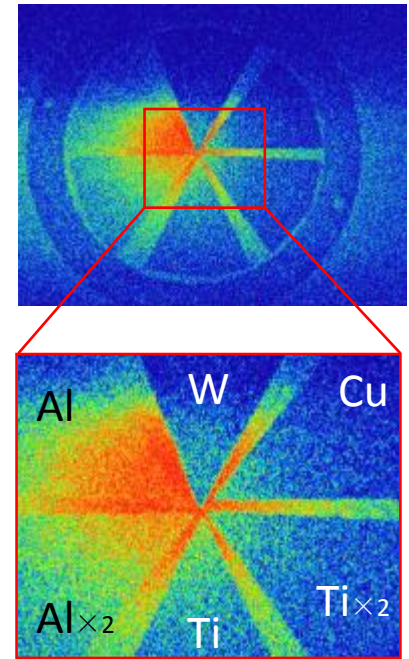
$E_{\text{max}} \sim 0.4$ GeV

P~70 TW

Pressure= 39 psi

$E_{\text{max}} \sim 0.3$ GeV

Betatron X-rays



Ross filters

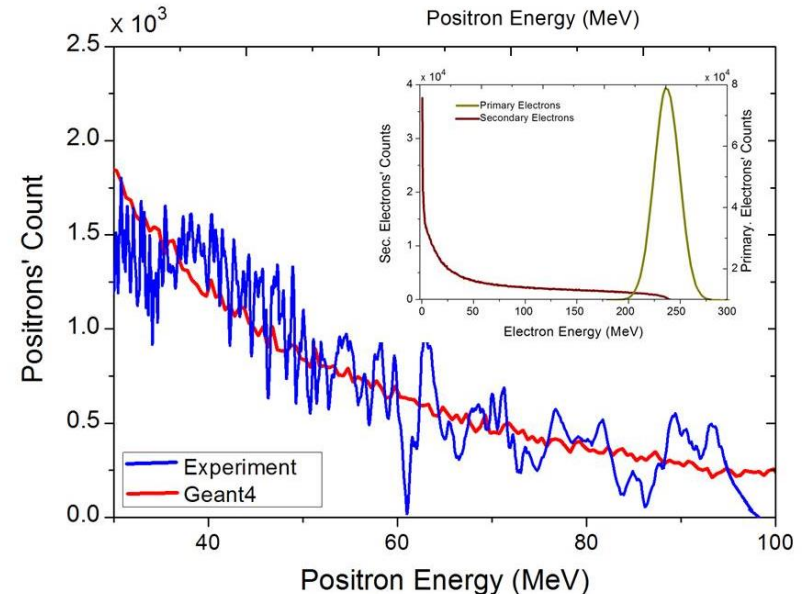
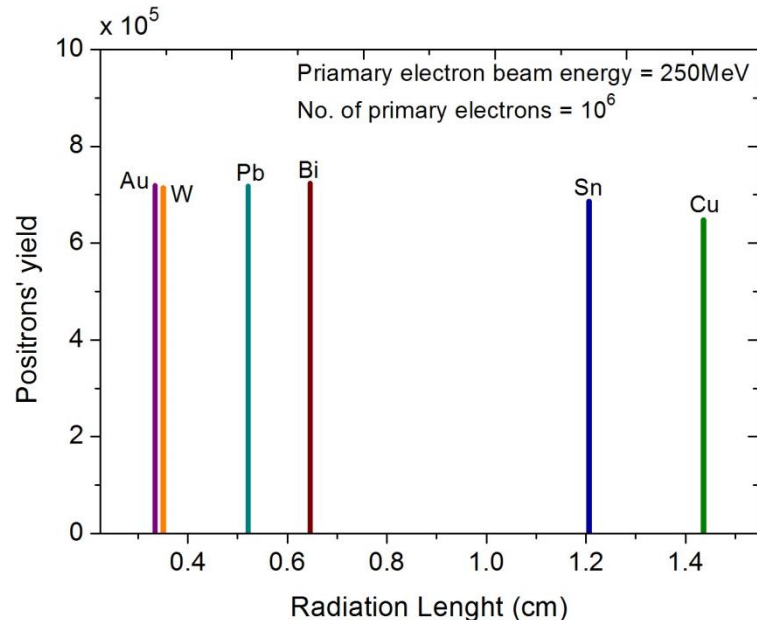
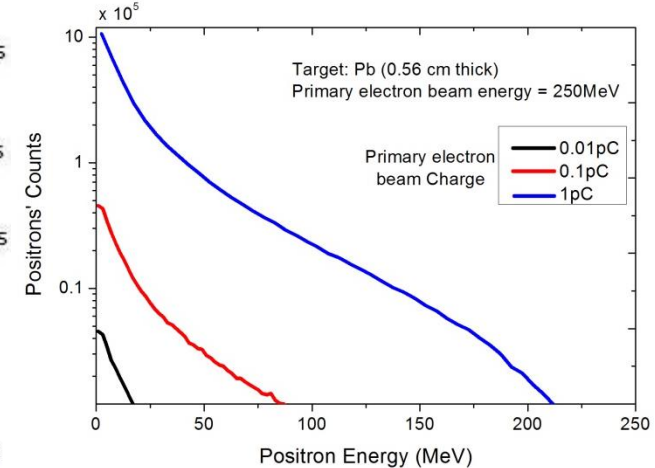
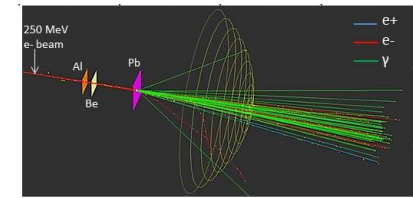
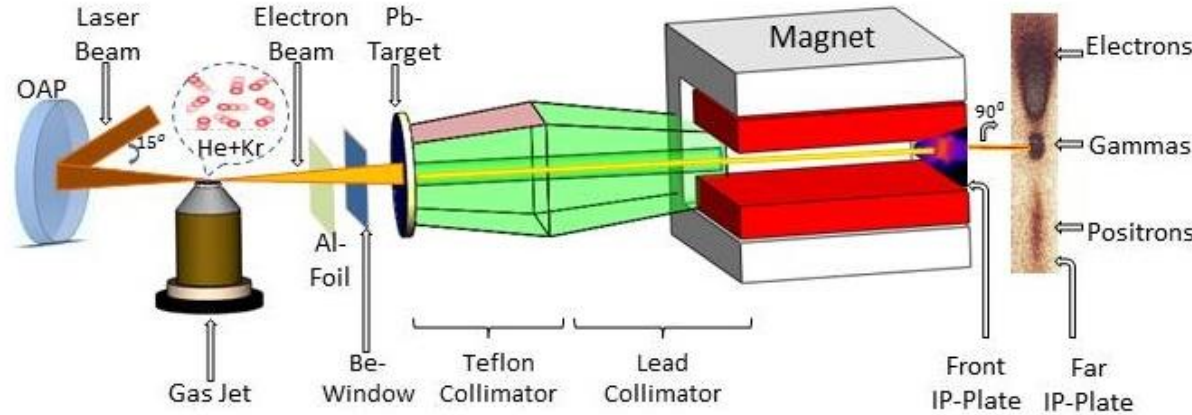
- Peak energy of electrons reaches to > 0.8 GeV
- Maximum Photon flux $\sim 10^9$ /shot with $E_c \sim 15$ keV

Positrons & γ rays generation via Bremsstrahlung

Q-Ain, Hafz* et al., (Physics of Plasmas) submitted 2017

Applications of slow positrons in SS phys.:

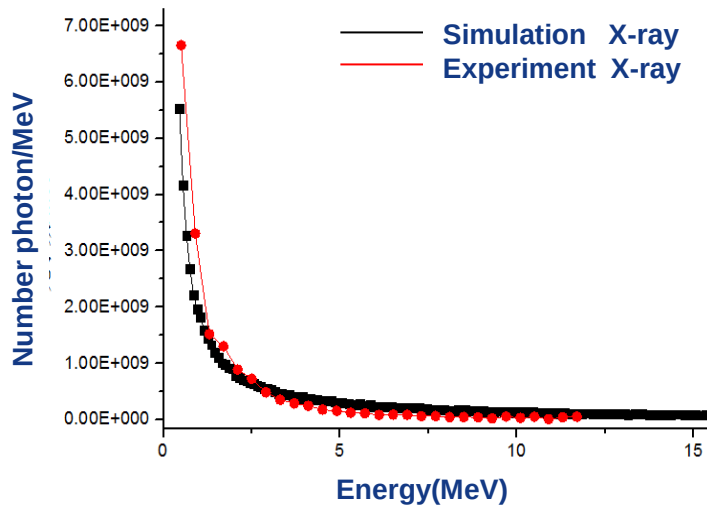
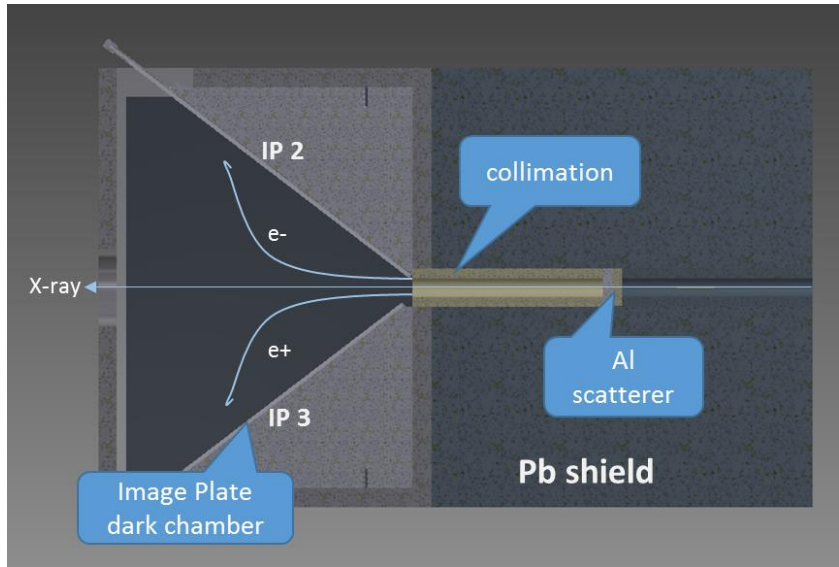
Positron annihilation spectroscopy and Surface physics





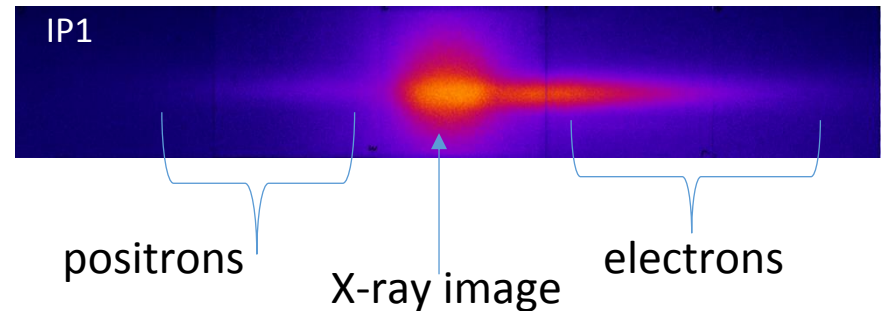
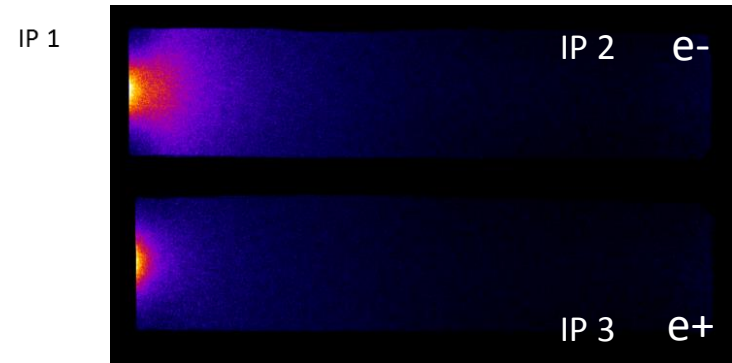
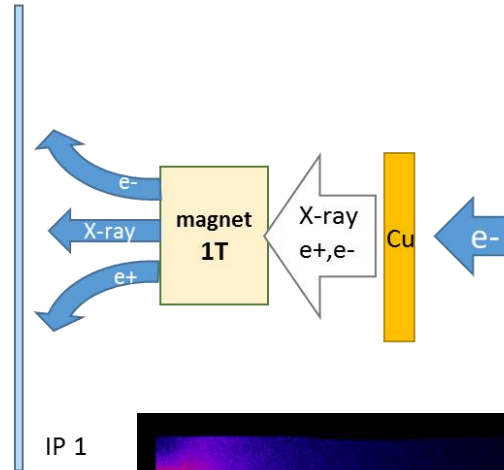
Applications of our electron beams

γ -ray spectrometer



Hu, Chen, Hafz et al., in preparation

Bremsstrahlung Radiation





Conclusions

- ④ **30-TW-60 TW and up to 120 TW pulses at SJTU are being used for LWFA experiments since 2014.**
- ④ **We generated 1.2 GeV high-quality electron beams by self-truncated ionization injection.**
- ④ **We generated secondary radiations and particles: keV betatron X-rays, up to 100 MeV positrons and MeV gamma rays by Bremsstrahlung.**