Laser driven high charge electron acceleration for X/γ-ray radiation

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Facility I ---IOP XL Lasers

~1 PW(30fs, 20 min.)

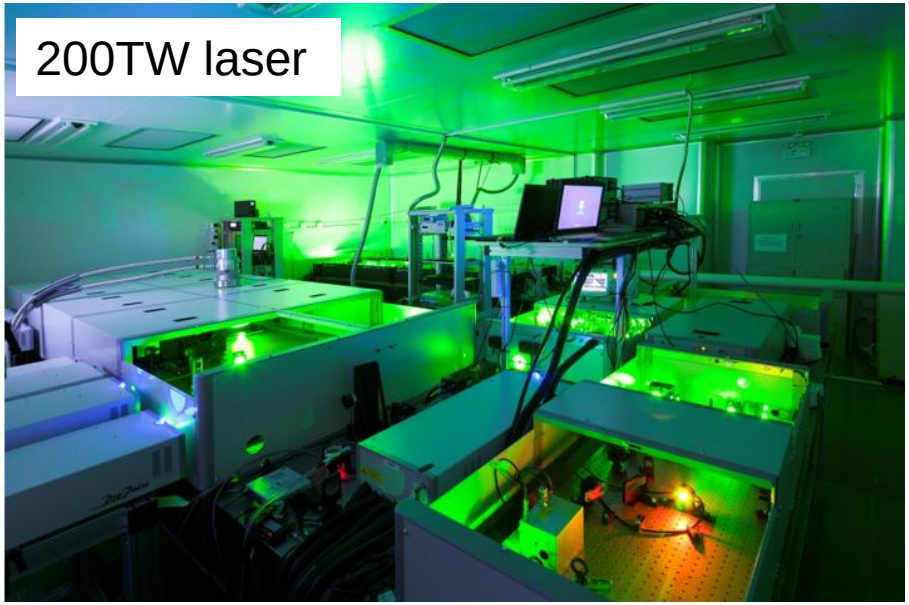
100TW (30fs, 0.1Hz)

20TW (30fs, 10Hz)

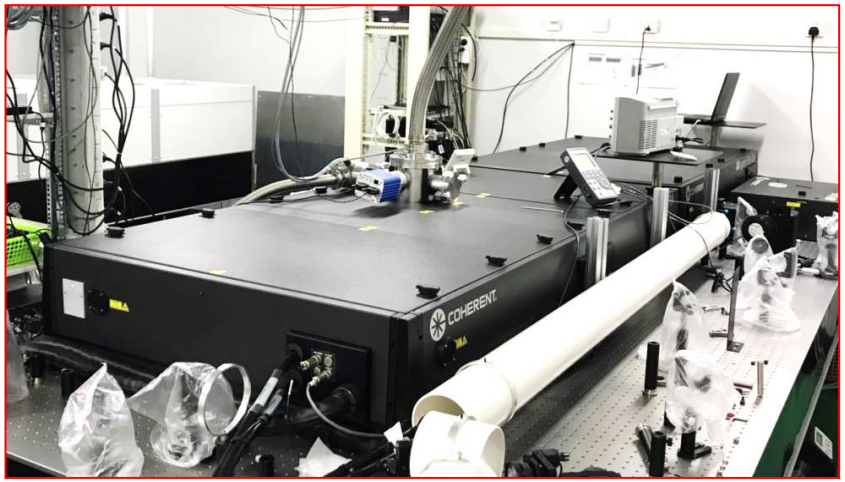
3 target areas

650 m^2

Facility II ---SJTU LLP



KHz, 20mJ, 30fs



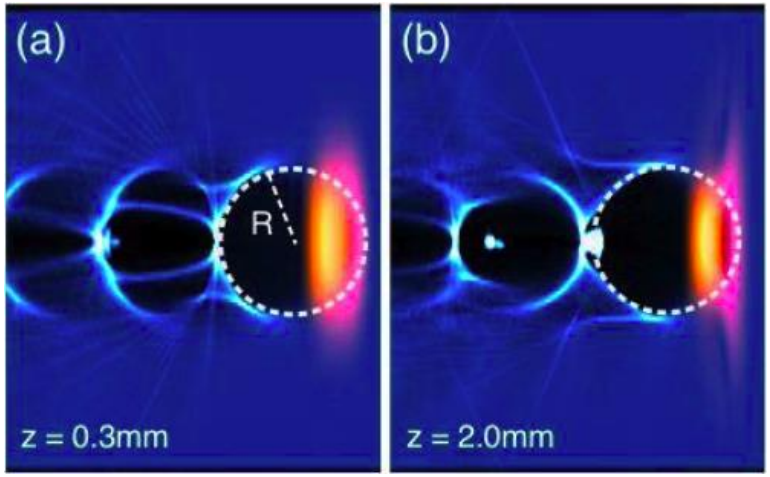
200+300TW in new building , 1PW in Huairou SECUF, and 2.5PW in TD Lee institute

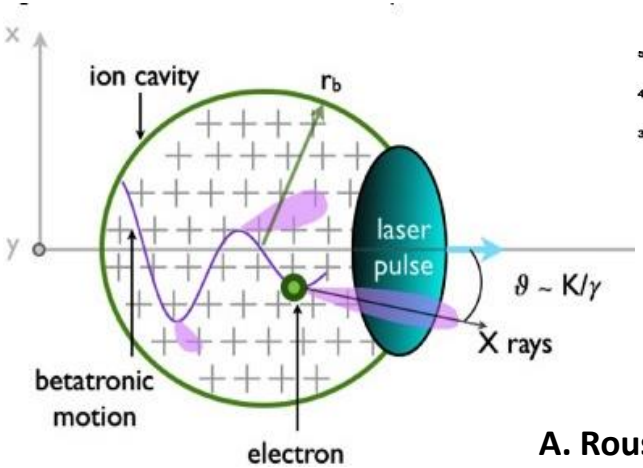
Outline

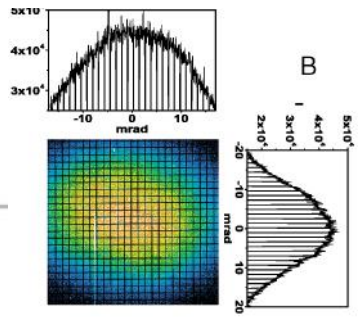
1. Motivation
2. High charge electron acceleration
3. Enhanced Betatron X/γ sources
4. Summary

Betatron radiation in laser acceleration

Laser-plasma accelerator + Plasma Wiggler → table-top Synchrotron Radiation





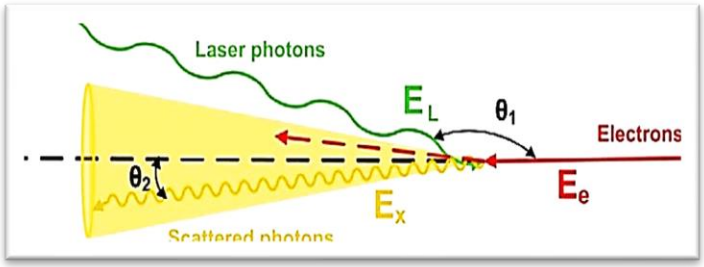


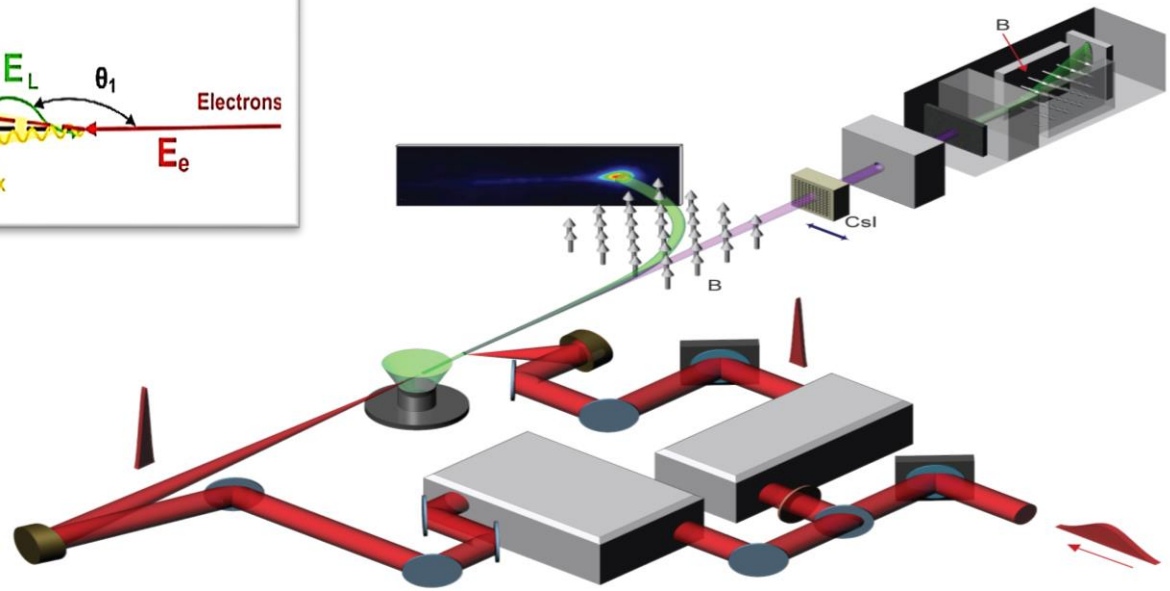
A. Rousse, PRL. 93, 135005 (2004)

Intense, compact, fs duration, natural synchronization

Electron Energy **Charge** Oscillation (amplitude/frequency)	→	Photon yield Photon energy Brightness
electron beam		radiation

Thomson Scattering based on acc. e⁻ beam





$$\hbar\omega_x = \hbar\omega_L \frac{2(1-\beta cos\theta_1)n\gamma^2}{1+{a_0}^2/2+\gamma^2{\theta_2}^2}$$

Back scattering（θ_1=180^0, θ_2=0）

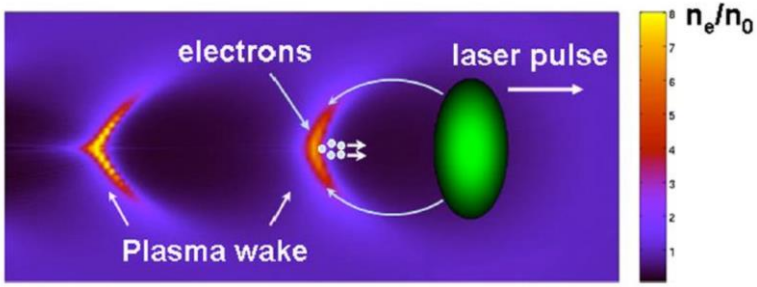
$$\omega_S \sim 4\gamma^2\omega_L$$

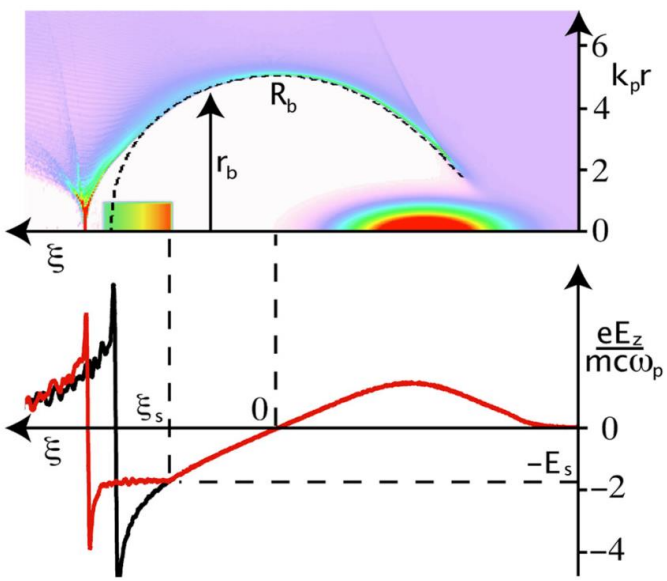
$$N_x = \frac{\pi}{3}\alpha N_0 N_e {a_0}^2 \frac{(1+{a_0}^2/2)(1-\beta cos\theta_1)}{\langle n\rangle(1+\overline{\beta_z})}$$

Photon yield of TS is linearly proportional with e⁻ charge.

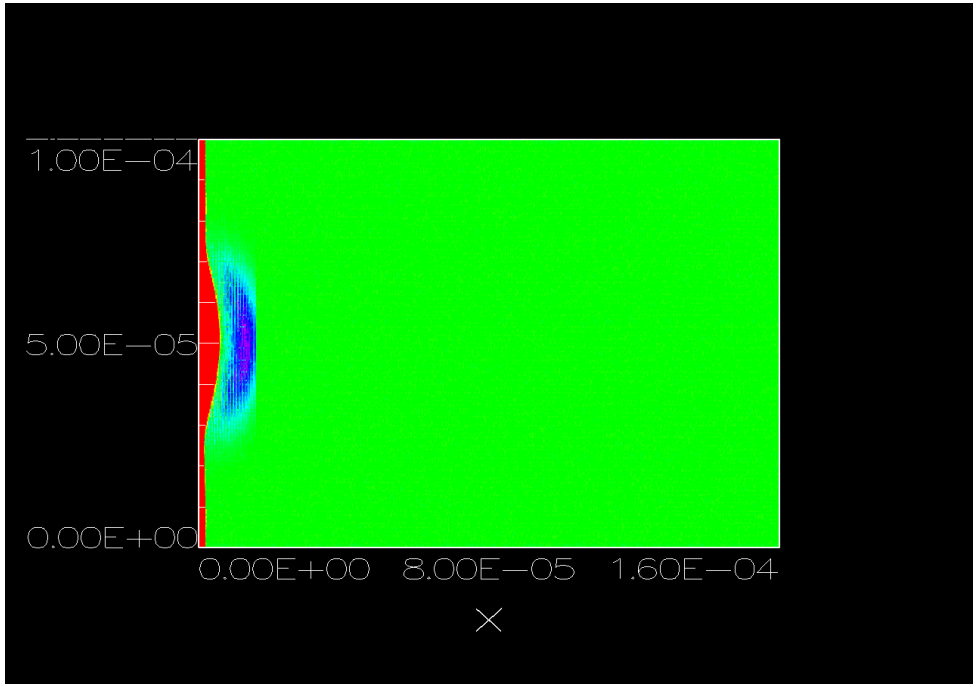
Bottleneck of acc. e⁻ beam charge

Beam loading effect
for bubble e⁻ acc.





M. Tzoufras, **PRL** 101, 145002(2008)



$$E_{max} \cong 1.7\left(\frac{P\,[\mathrm{TW}]}{100}\right)^{1/3}\left(\frac{10^{18}}{n_e\,[\mathrm{cm}^{-3}]}\right)^{2/3}\left(\frac{0.8}{\lambda_0(\mu\mathrm{m})}\right)^{4/3}$$

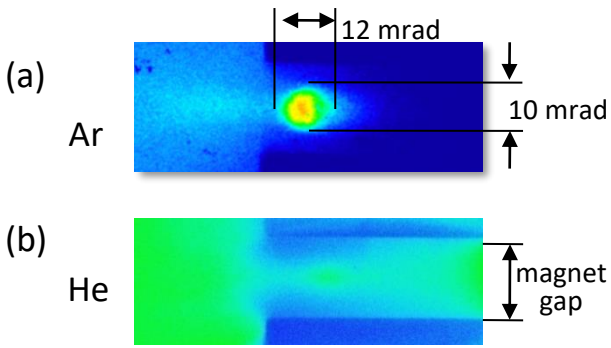
$$N \approx \frac{8/15}{k_0 r_e}\sqrt{\frac{P}{m^2c^5/e^2}} \approx 2.5\times10^9\,\frac{\lambda_0\,[\mu m]}{0.8}\sqrt{\frac{P[\mathrm{TW}]}{100}}$$

How to break the beam loading effect?? Use other acc. methods

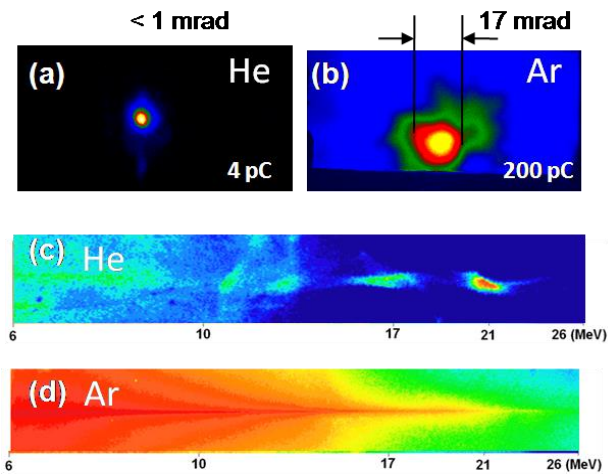
e- & Radiation enhance-I: DLA clusters

3TW: N=2x10^8 （>3keV）
10mrad, CE↑~40

Betatron x-ray

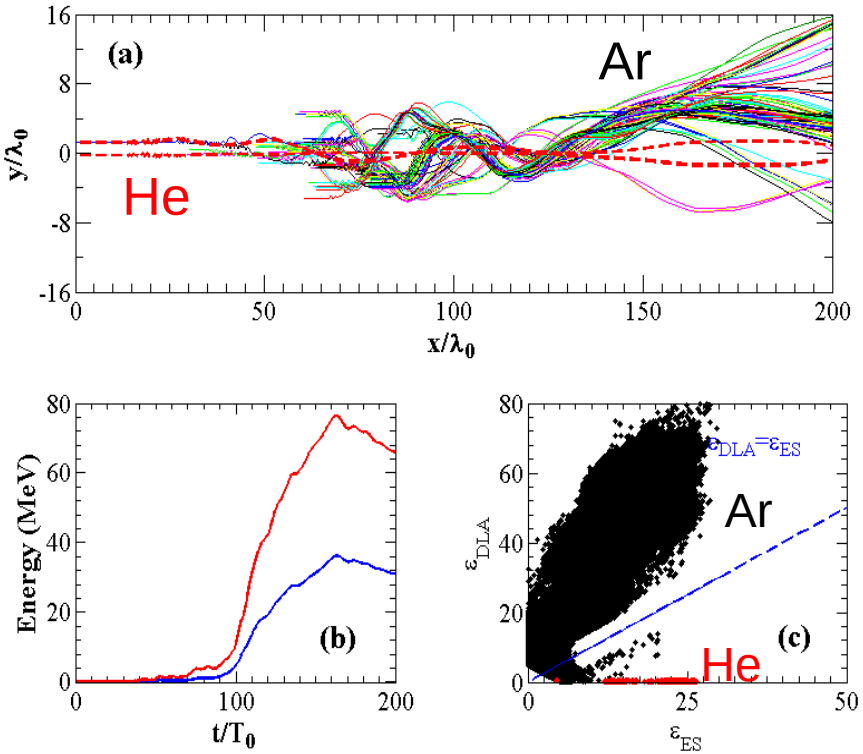


Electrons



200pC >Beam loading: 69pC

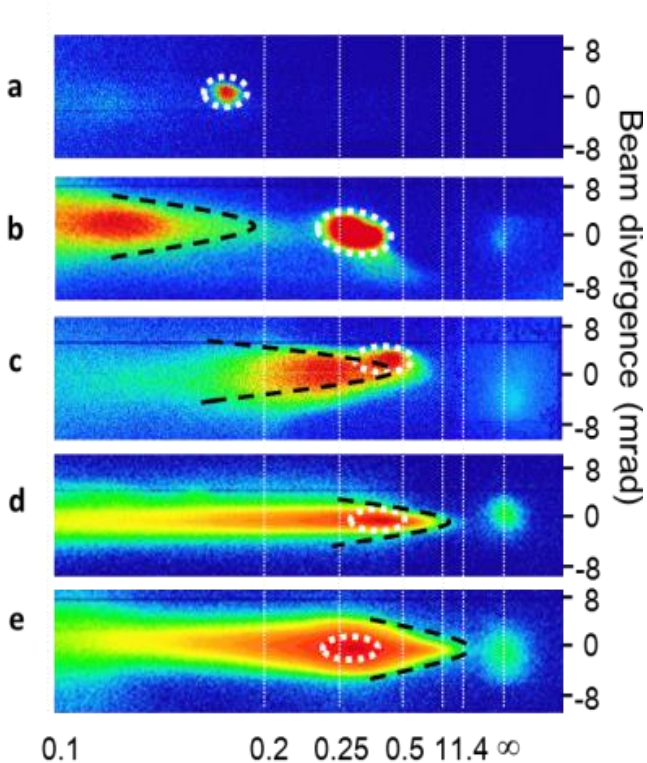
Simulation

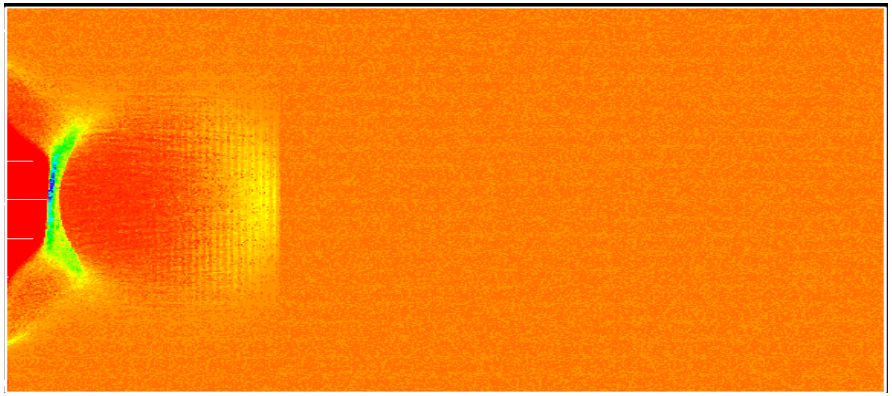


Sci. Reports 3, 1912(2013)

DLA will be important mechanism for cluster. It leads to much higher e$^-$ charge and larger oscillation amplitude.

e- & Betatron enhance - 2: Oscillation Injection





B=2×10^{23} phs/s/mm^2/mrad^2/0.1%BW

E_{max}= 1.4 GeV
E_{center}= 300 MeV
Q = 600pC > BL

Betatron E_{cri}= 15 keV
Photon = 4.5×10^8
Divergence = 6 mrad
Size=4 μm

$$\Delta E(\mathrm{GeV})=1.7[P_{(TW)}/100]^{1/3}[10^{18}/n_e]^{2/3}[0.8/\lambda_0]^{4/3} \sim 0.67 < 1.4\ \mathrm{GeV}$$

We assume that the high quality electron bunch comes from the 1st e- bunch, and the strong x-ray radiation comes from the 2nd beam with much high energy, large charge and large oscillations.

W. C. Yan, L. M. Chen, **PNAS** 111, 5825(2014)

Double Injection for γ-rays

Envolution of plasma density

PIC parameter:

Laser: Callisto

P=100 TW

w_0=18 μm

τ=60 fs

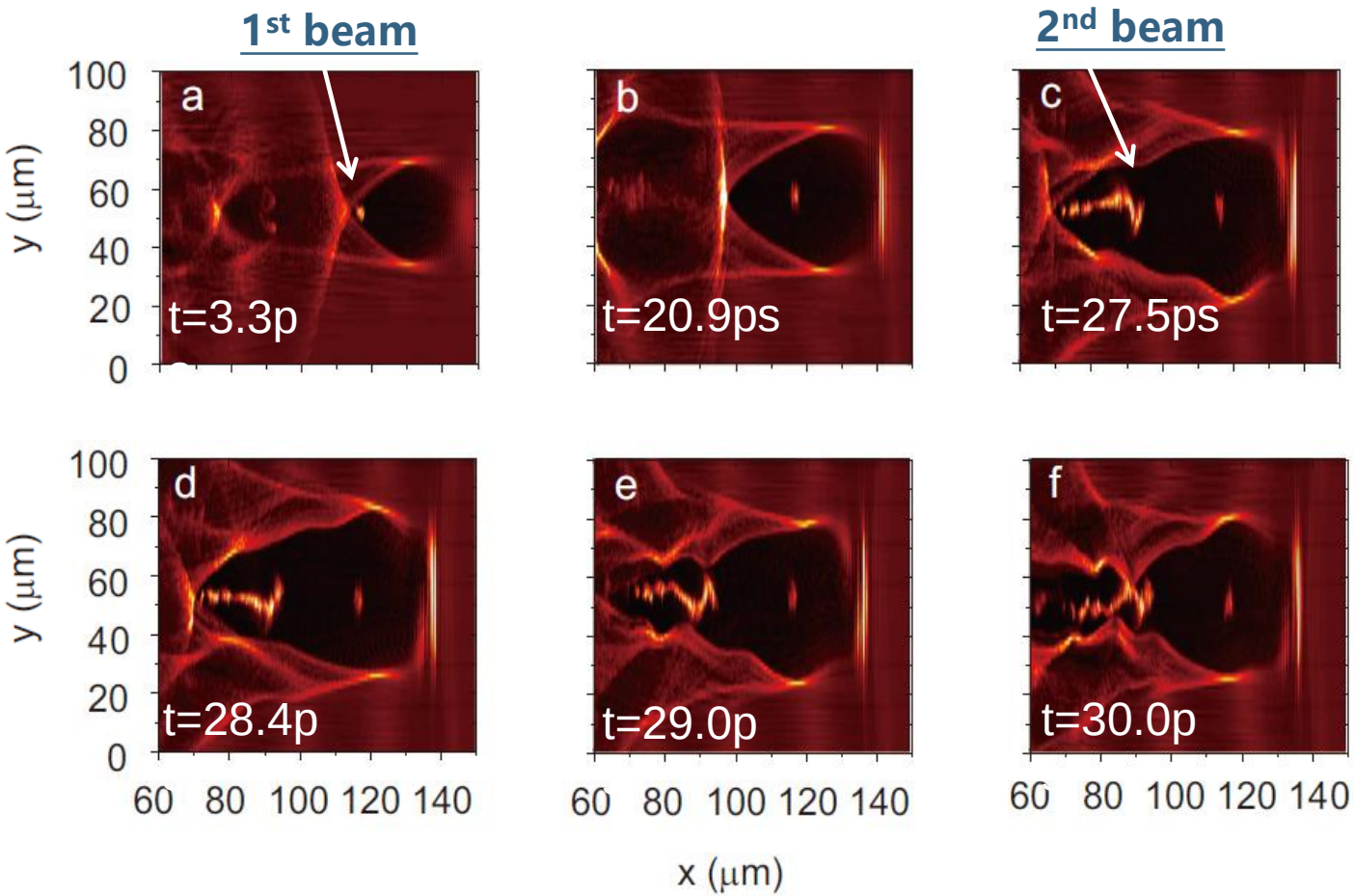
a_0=3.6

Plasma:

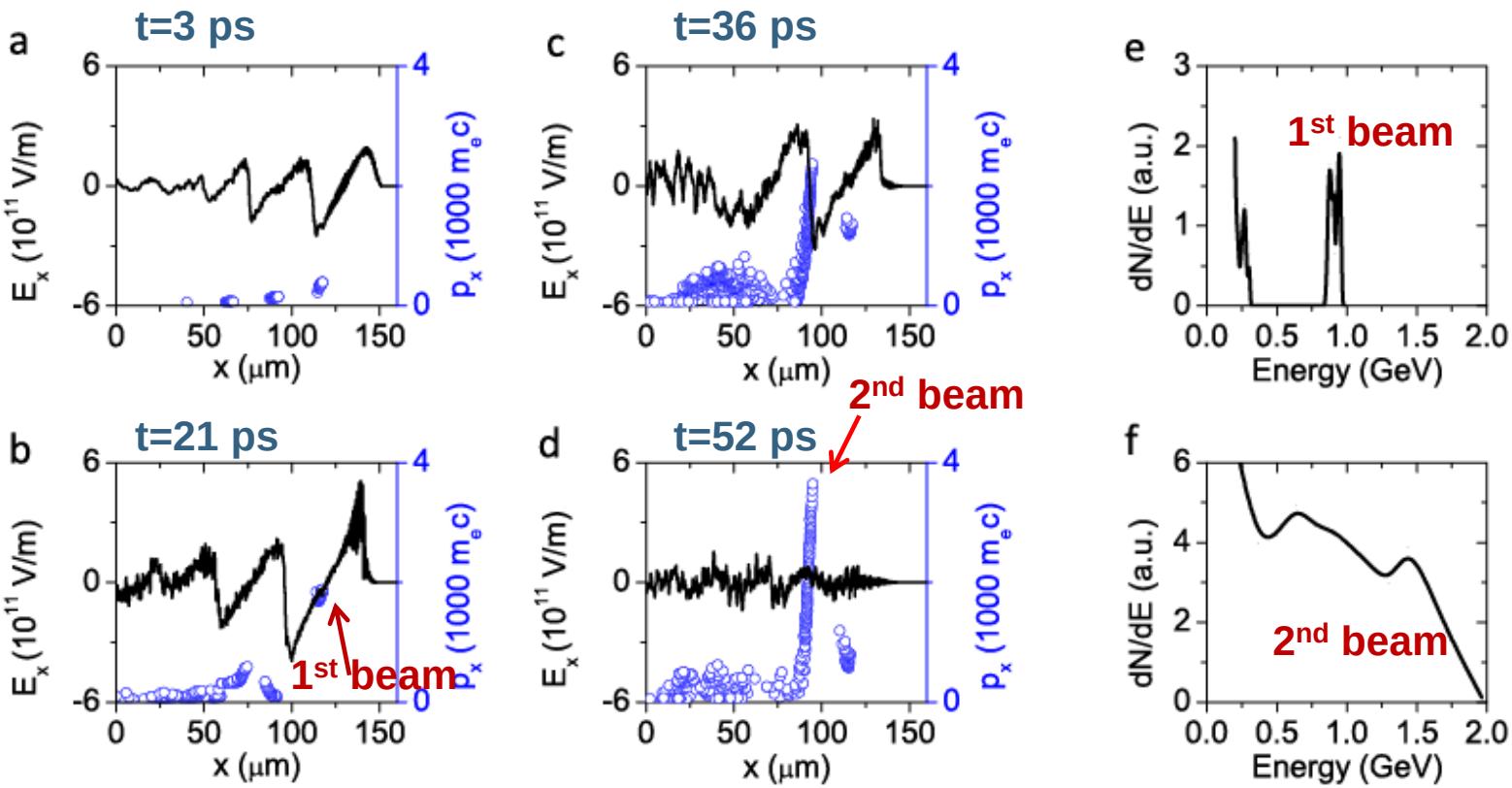
$n_e=2\times10^{18}$ cm^{-3}

Matched bubble:

1.3×10^{18} cm^{-3}



Comparison of energy and charge



1st beam:
Max. Energy γ=2000

$\gamma \uparrow$

Sharp field distribution

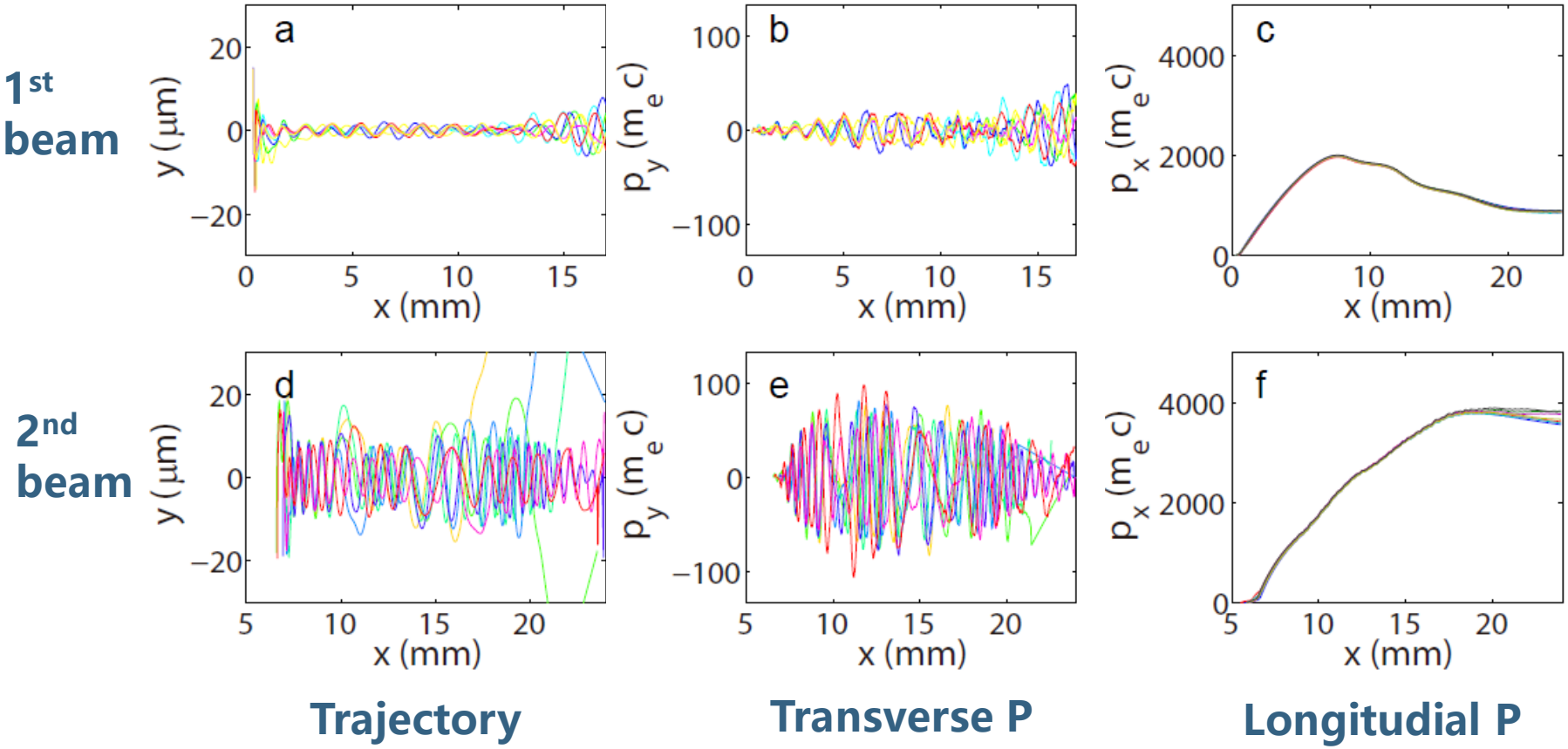
2nd beam
Max. energy γ=4000

Smoothly field

$N_{e2}/N_{e1} \approx 10$

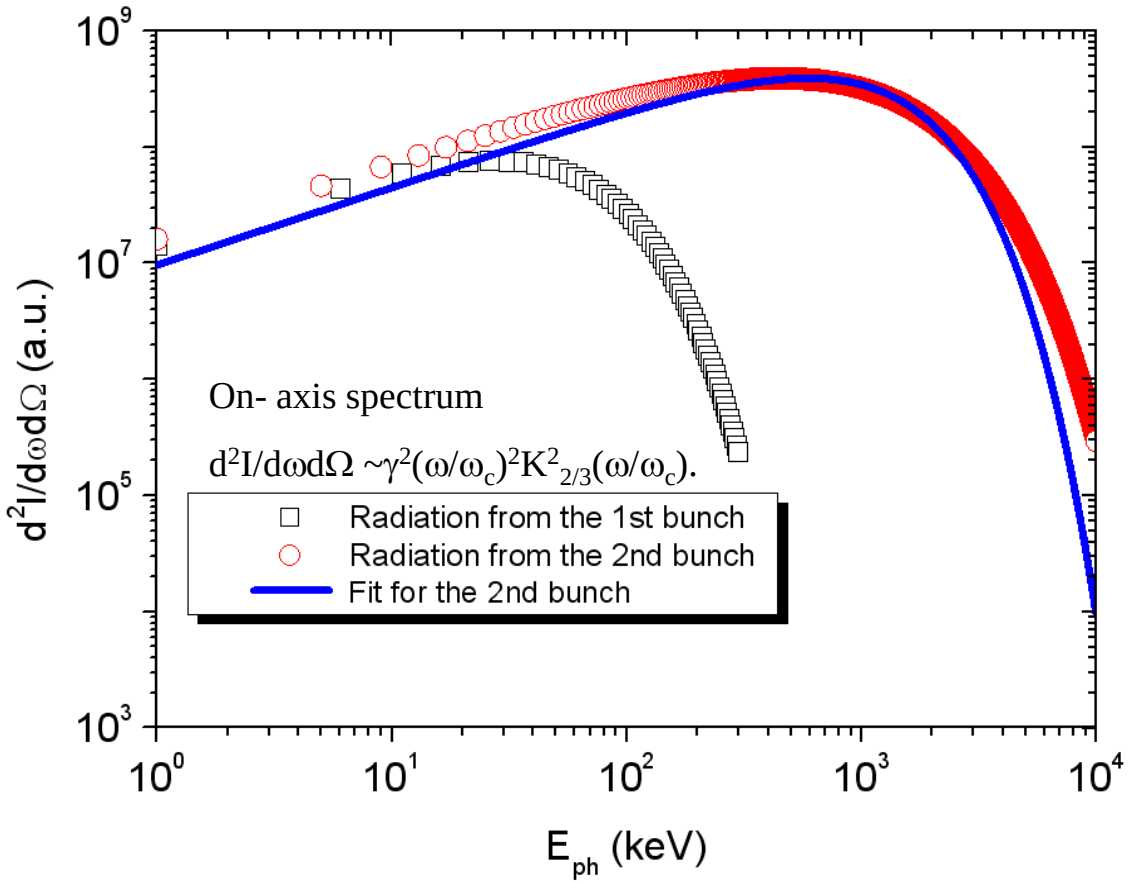
$N_e \uparrow$

Comparison of oscillation and duration



1st beam:	r_β = 1 μm	×		**Quickly reduce**
2nd beam:	r_β =10 μm	r_β ↑ √	N_β ↑	**Maintain >20 ps**

Intense Betatron γ-rays



1st pulse: E_c ~ 80 keV

2nd pulse: E_c ~ 1.2 MeV (max. ~ 10 MeV)

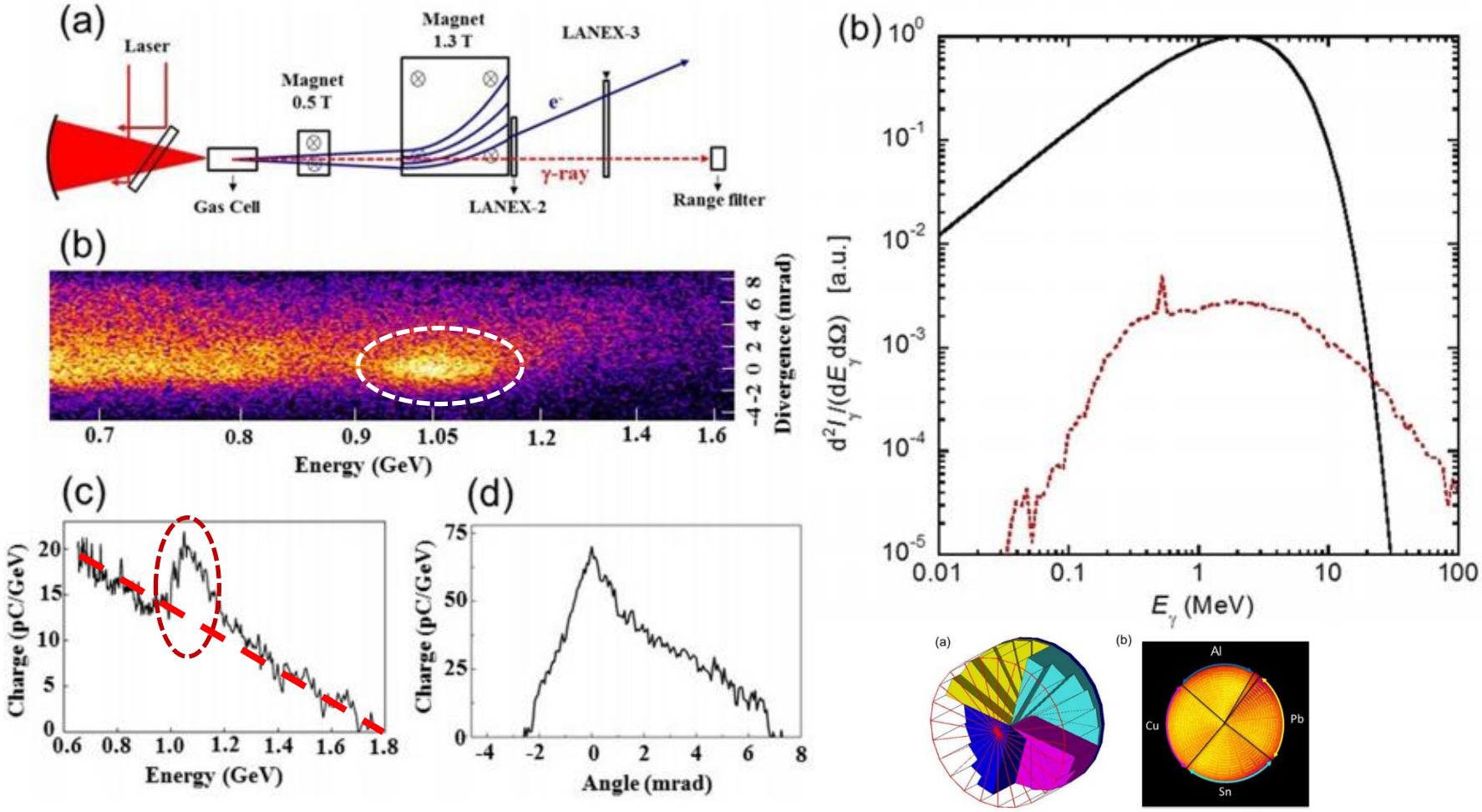
Photon-nuclear reaction

Sci. Reports 6, 30491(2016)

Betatron γ-rays experimental demonstration

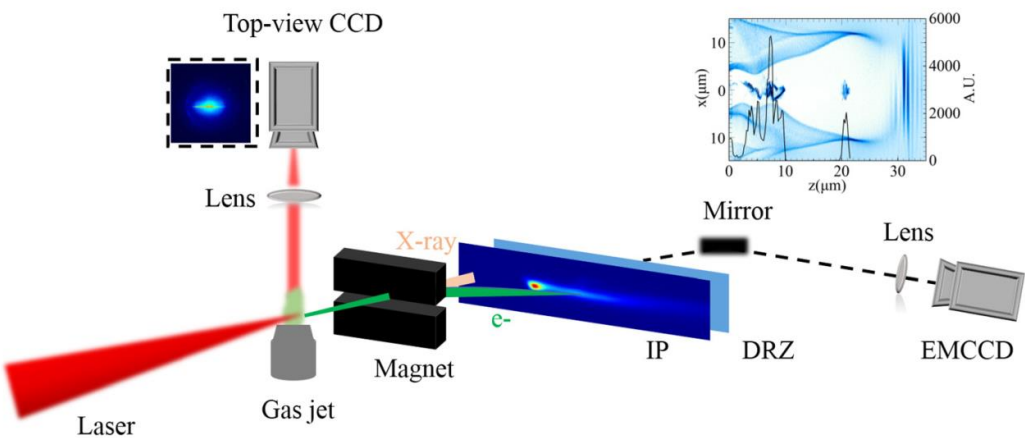
PHYSICS OF PLASMAS **23**, 073105 (2016)

Measurement of angularly dependent spectra of betatron gamma-rays from a laser plasma accelerator with quadrant-sectored range filters

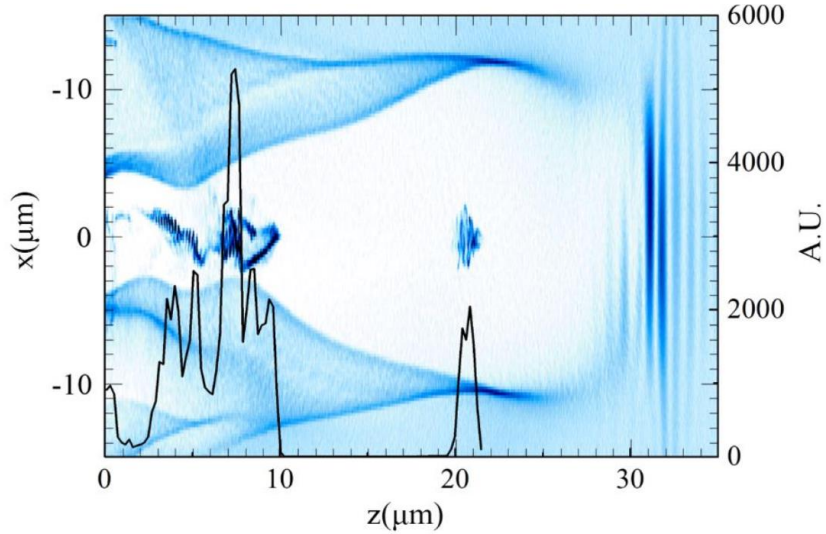


Experimental 20 kA electron beam

SJTU 80TW-laser

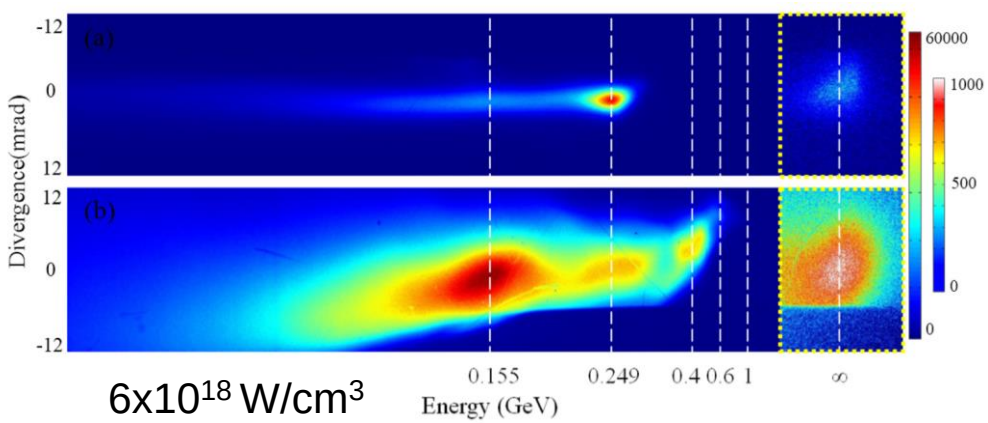


Experiment Setup



Using oscillation injection, 1st to 2nd beam is 5fs to 28fs, with charge 1:10 in simulation.

5×10^{18} W/cm^3



6×10^{18} W/cm^3

Experiment:

1st beam: 249MeV, 68pC

2nd beam: 0.6GeV, 620pC(>100MeV)

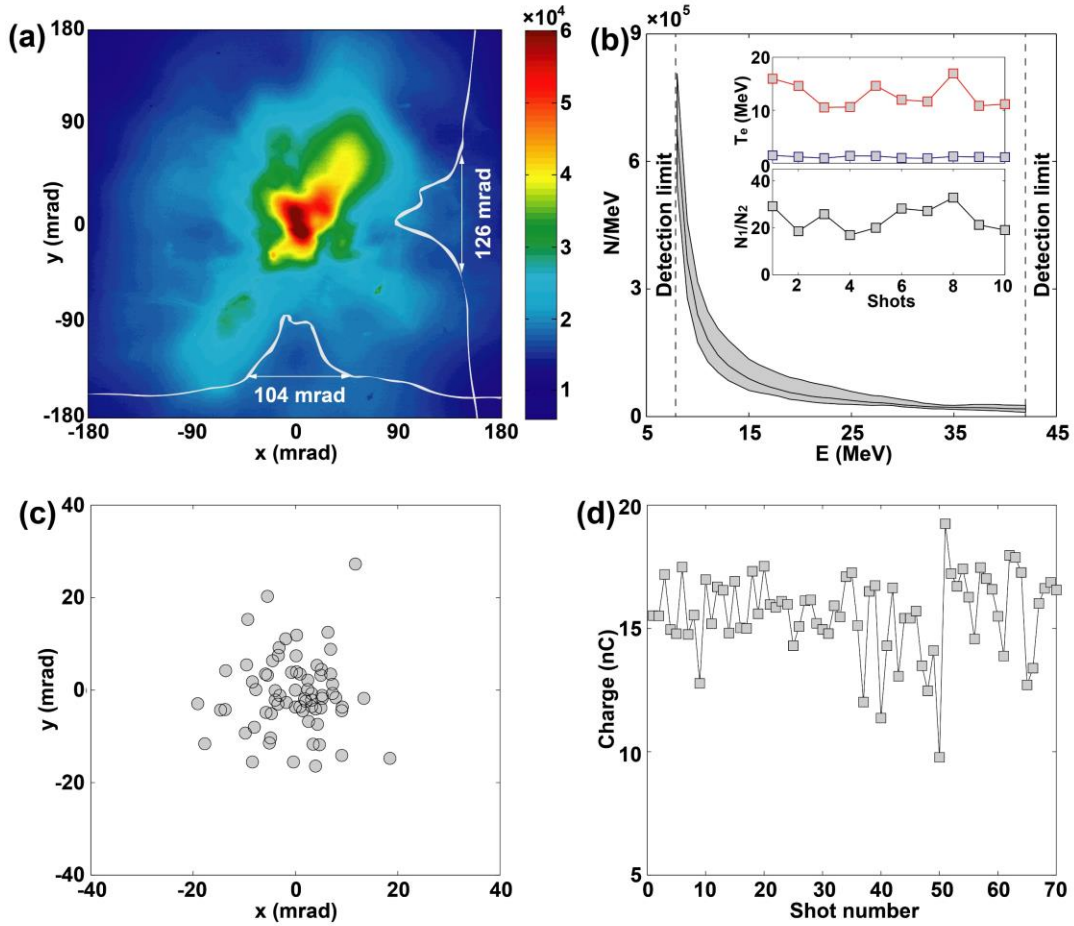
~1.5xbeam loading charge(360pC)

~10 x 1st beam charge

Phys. Plasmas 24, 023108(2017)

e- & Betatron enhance - 3: DLA- NCD target

SJTU 100TW-laser **Experiment results** (to be submitted)



(a)Beam profile;
(b)Electron spectrum
(c)Pointing stability
(d)Electron charge

Electron spectrum:
Te1=1.19±0.19 MeV;
Te2=12.88±2.41 MeV
N1/N2 = 23.90±5.42

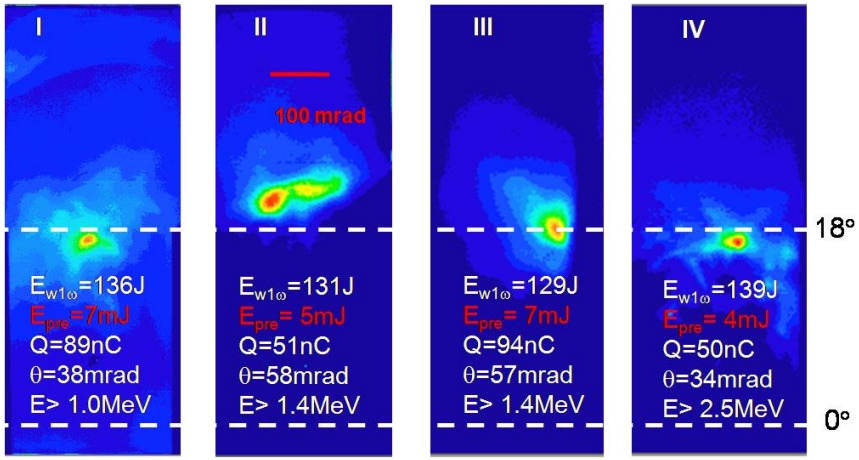
Beam Charge: 15.59±1.68 nC
>>beam loading

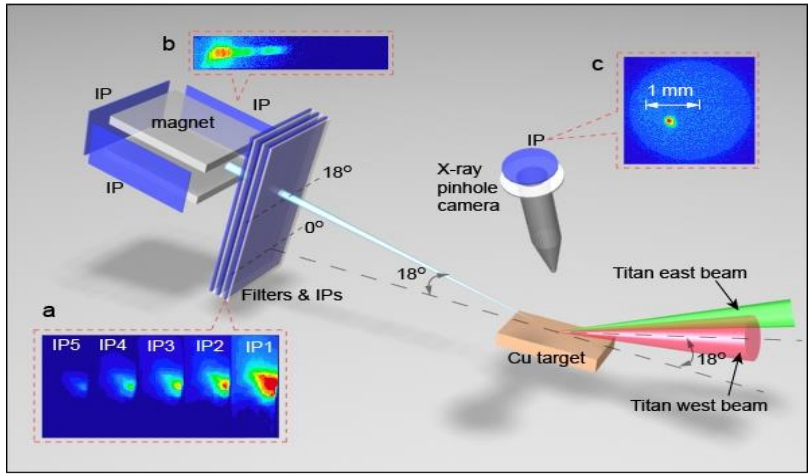
Laser/electron C.E.:
（E >1MeV）: ~5.6%

Use 100TW laser pulse interacting with near-critical-density (NCD) target, We obtained collimated ten's MeV electron beam with extreme high charge (16nC).

4. Ultrahigh charge e-beam charge from solid

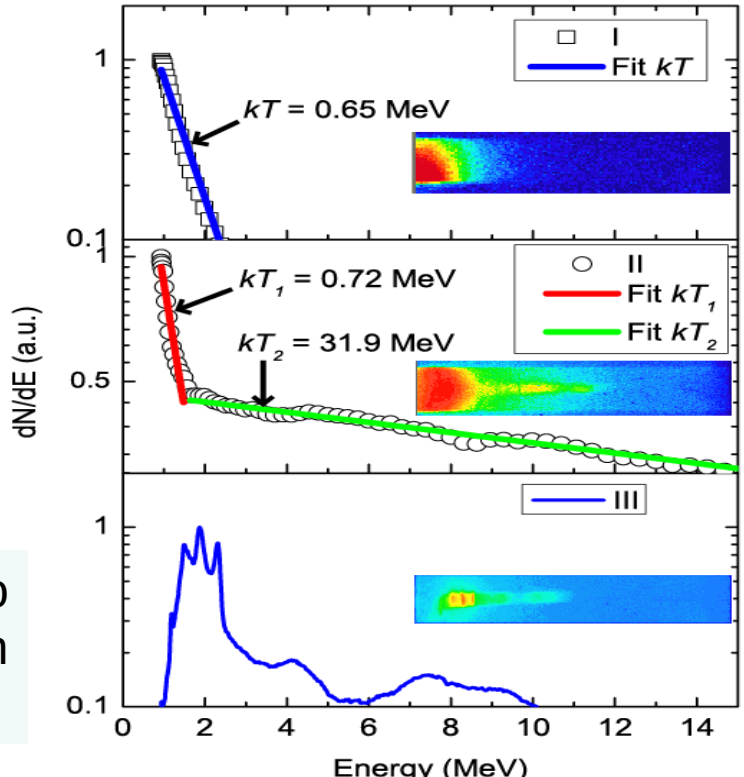
With suitable pre-pulse E_{pre} ~ 5 mJ





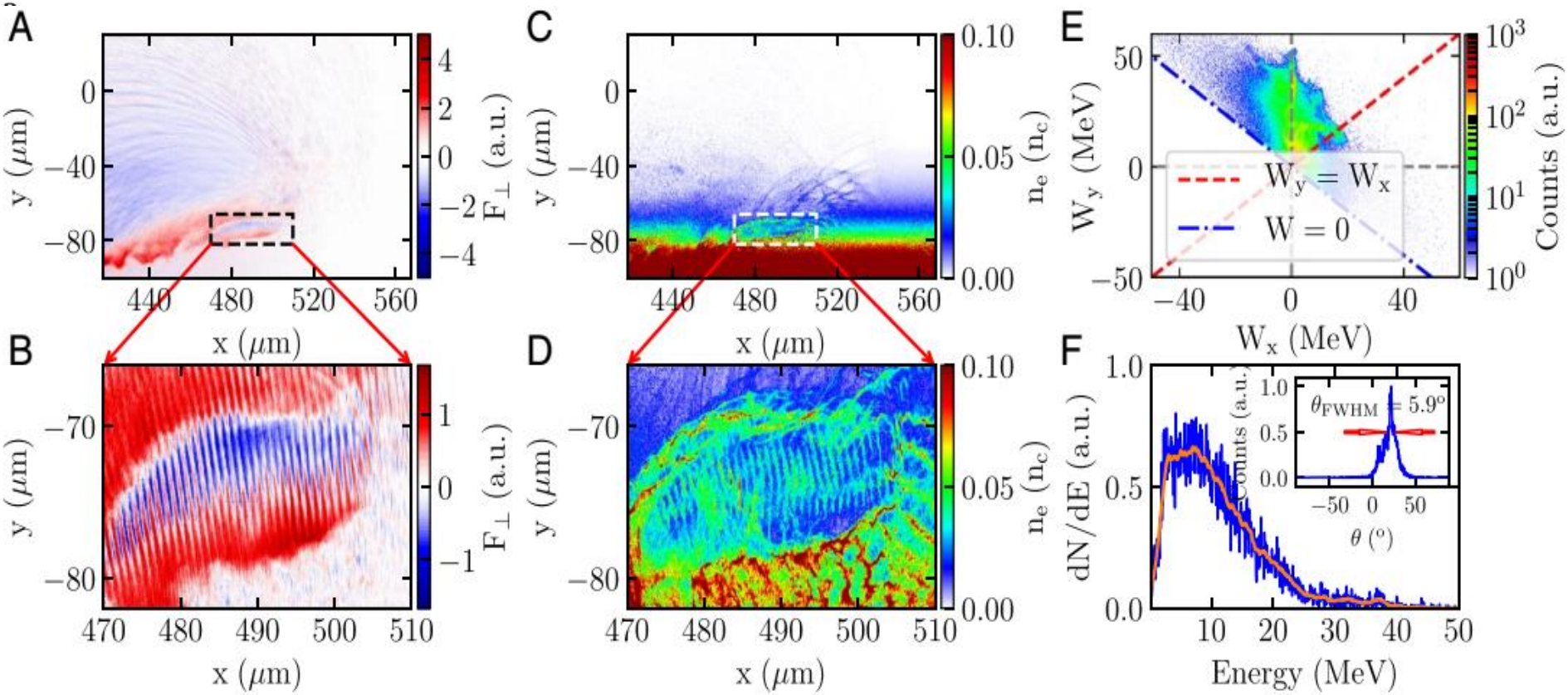
- Collimated: < 2°
- Directional: laser specular
- Charge: ~100 nC !

γ-ray bremsstrahlung source:
Yield: 2 x 10^{11}
Duration ~ ps, Size < mm



Suitable preplasma help ps laser to accelerate high charge e-beam, which lead to ultra-intense γ-ray sources.

DLA effectively driven e-beam from solid



Y. Ma, L. M. Chen* et al, PNAS 115, 6980 (2018)

Summary…

- High charge electron acceleration beyond beam loading effect is archived via “Oscillation Injection” with higher plasma density.

- DLA would be important mechanism for high charge electron acceleration, using cluster, NCD or even solid targets with high plasma density.

- High flux X/γ-ray emission is obtained via high charge electron induced effective betatron oscillation.

Thank you for your attention!

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